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PROJECT FLAMBEAU...

An Investigation of Mass Fire (1964-1967)

Final Report—Volume III : APPENDIXES

A. Preparation of Test Plots for Fire Behavior Studies Using Wildland Fuels to Simulate Urban Conditions, by *Theodore G. Storey*

B. Tree Weights and Fuel Size Distribution of Pinyon Pine and Utah Juniper, by *Theodore G. Storey*

C. Gas Analyses in Large Fire Experiments, by *A. F. Bush, J. J. Leonard, and W. H. Yundt*

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1969

FOREST SERVICE
U.S DEPARTMENT OF AGRICULTURE
P O BOX 245, BERKELEY, CALIFORNIA 94701

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

99

SUMMARY

Preparation of Test Plots for Fire Behavior Studies Using Wildland Fuels to Simulate Urban Conditions, by Theodore G. Storey:

Studies in forest fire behavior by the Pacific Southwest Forest and Range Experiment Station have included a series of experimental fires made for the U.S. Defense Atomic Support Agency and U.S. Office of Civil Defense. Piles of uprooted pinyon pine and Utah juniper were set up, dried, instrumented, and then burned at a test site along the California-Nevada border. The piles represented fuel loading and spacing of houses in residential areas of typical cities in the United States. In each plot, the piles were ignited simultaneously so as to obtain a high-intensity fire.

In the 1964-67 experimental fires, the Station used some unique methods to select the test site, clear the land, prepare the plots, and determine the amount of fuel. By using entire trees for fuel, including roots, the cost of gathering fuel was reduced markedly. This paper describes the methods used and includes recommendations of what might be done in future work of this type.

Candidate test sites within the pinyon pine-juniper type were chosen after a reconnaissance survey from light aircraft, study of aerial photos, and follow-up ground inspection. Two sites were selected: the 45,000-acre Basalt Site north of U.S. Highway 6 and west of Basalt, Mineral County, Nevada; and the 15,000-acre Mono Site south of California Highway 31, Mono County, along the California-Nevada border, and northeast of Lee Vining, California. After the sites were chosen, tree stands were tentatively matched with plot fuel requirements.

Trees in each of the 14 selected areas were lifted, transported, and piled to furnish the fuel for burning. The job of plot preparation was handled by a private contractor. The test fuel beds were built by arranging pinyon pine-juniper trees in piles covering about 2,000 square feet and standing 6 or 7 feet tall. After fuel piles were completed, they were left to dry. Plots were to be burned when their average moisture content approximated that of wood in buildings. Before burning, each plot was heavily instrumented to measure characteristics of the fire and its environment.

The following conclusions were drawn on the basis of the work done:

1. Experience to date in preparing, conditioning, and burning experimental fires using pinyon pine-juniper debris has been favorable. The debris dried rapidly, permitting early burning. Weather conditions were not particularly a problem in the field work.

2. Some difficulty was encountered in writing the clearing contract and communicating with prospective bidders so as to get the results wanted. In future work of this type, extreme care should be taken in writing the contract requirements so that they are unambiguous.

3. The existing tree weight-crown diameter relationships for pinyon pine and Utah juniper may be directly applicable to these and to other species of pinyon pine and juniper growing elsewhere in the Southwestern United States.

4. Good aerial photos are essential for selecting sites and prospective plot areas.

5. The technique of clearing and the individual types of equipment and equipment teams developed and used by the contractor appeared to be equal to the job.

Tree Weights and Fuel Size Distribution of Pinyon Pine and Utah Juniper, by Theodore G. Storey:

To aid in timber cruising for preparation of test plots and in interpretation of fire behavior, we gathered information on fuel weight and size distribution of pinyon pine and Utah juniper trees. This paper describes how trees of these two species were selected and sampled at the test sites, the analytical procedures used, and the results obtained in relating weight of fuel to size and to dimensions, and in determining distribution of fuel weight.

Sample pinyon pine trees were selected from three sites in the study areas: Pizona Site, on the Inyo National Forest, Mono County, California; Basalt Site No. 1, Mineral County, Nevada; Basalt Site No. 2, Toiyabe National Forest, Nevada; and Mono Site, Mono County, California.

On most sites, trees were stratified into four broad stem-diameter or crown-diameter classes to cover the range in tree sizes found. Trees were selected randomly from each diameter class in proportion to the frequency of trees in the class. Each sample tree was photographed; measured for height, maximum crown diameter, and average crown diameter; uprooted; and weighed.

A process of data plotting and curve-fitting indicated that tree weights of pinyon pine was correlated with each of the four independent variables studied: maximum crown diameter, average crown diameter, tree height, and stem diameter at 1 foot. Regression equations were computed for each of the four relationships and the coefficient of determination and standard error of estimates for each were calculated. Essentially the same type of analysis used for pinyon pine was applied to Utah juniper with similar results. A similar curve was found to apply for estimating ovendry crown weight and ovendry root weight from each of the same four variables. A regression equation also was computed for ovendry root weight on ovendry tree weight.

On the basis of the finding, we concluded that:

1. Dry tree weight, dry crown weight, and dry root weight are closely correlated with maximum crown diameter, average crown diameter, and stem diameter at 1 foot for pinyon pine, and with maximum crown diameter and average crown diameter for Utah juniper, which has multiple stems.

2. About 25 percent of the total dry weight of small pinyons may be in the needles; another 25 percent is in twigs and rootlets 1/2 inch or less in diameter.

3. The fuel size distribution of juniper roots was not determined, but sample data on the total root weight of juniper are available. An estimate of the distribution of this weight, by size class, can be obtained by applying the data on distribution of pinyon roots.

4. The fuel size distribution curves for the small pinyon and small juniper crowns paralleled one another closely at fuel diameters larger than 1/4 inch.

5. Fuel size distribution among branches of identical girth from larger trees of either species appears to vary only slightly.

Gas Analyses in Large Fire Experiments, by A. F. Bush, J. J. Leonard, and W. H. Yundt:

Large experimental fires make it possible to measure fire characteristics. Such fires allow a range of prescribed initial conditions, such as fuel moisture, loading, and geometry. They may be instrumented to yield measurements for evaluation of fire behavior and environmental effects.

In recent experiments, a limited program of gas sampling and analysis was carried out to provide some of the desired data on life hazard in the open (fuel bare) regions between piles or burning units and in regions which shelter location might be forced to rely for ventilation. More recent experiments were instrumented expressly to provide further life hazard information in the zone of most probable human exposure.

This paper reports data from 13 experimental fires--six from the series 460, Mono County, California and 760, Mineral County, Nevada, and ranged in array size from 1 to 342 piles. Each pile weighed about 20 tons, and measured 46.7 feet square, and 7 feet tall. Fuel was primarily pinyon pine and Utah juniper trees. Results are also reported for four fires from series 380 and two from series 428, described as heavy fuel plots and light fuel plots. One experiment reported is a two-story house fire.

The sampling system used in Test Fire 760-12, burned on September 29, 1967, consisted of a bank of continuous analyzers sequencing six inlets. Gases from the inlets were drawn through separate tubes out of the fire to the instrument trailer about 400 feet away. Pressure in the six lines at the points of sample removal were kept constant.

The gas sampling equipment used in all experimental fires except 760-12 involved three separate types. The continuous sampling system had a main pump to draw samples through aluminum tubing. Two instrumental analysis systems drew their samples from the main line. The second system, sequential grab samplers, consisted of sets of five 300-cc. double stop-cock Pyrex gas bottles which were evacuated to 1 mm Hg. or less before the fire and opened remotely at selected times by electric solenoid valves. The third system, integrating samplers, consisted of a set of six midget impingers, a self-contained pumping system, and a gas collection reservoir. The pumps draw sample gases through each of the impingers at a known flow rate between 0.5 and 1.0 liters per minute.

Systems developed to sample and analyze gases from experimental fires provided data that appear to be consistent with the general pattern of behavior of the fires and with other data collected. The capability of the systems used in fires before 760-12 was limited by the amount of continuous analysis equipment available, but it was partially remedied by the development of more sophisticated devices in later fires.

On the basis of the findings, the following conclusions can be drawn:

1. Gas analysis data is of importance in defining fire behavior, and comparing between experimental fires, in evaluating mass fire related hazards, and in testing and providing valid data for fire models.

2. The measurement of water vapor concentration is essential to an understanding of mass fire, from the standpoint of defining internal environmental conditions, defining total human exposure, and as a means of relating the combustion process to fuel parameters and true energy release rate.

3. Dilution ratios based upon carbon dioxide concentrations or other gas component measurements can provide broad insight for study of interactions within the mass fire system and may be used as the basis for empirical relationships between measurable parameters and complex effects associated with them. In addition, dilution ratios may provide a basis, with other measurements, for the understanding of mass transport in the fire environment.

4. Smoke analyses are required in order to better understand the gross combustion process, and to evaluate hazard to human life. Photomicrographs of particulate material in the atmosphere of three fires are shown. These give indication of the nature of the suspended residue left in the air by combustion of forest and urban fuels.

5. Analyses of gases in the streets of large experimental fires to date suggest that sufficient oxygen for survival is available at ground level in such locations and that noxious gas concentrations are generally below hazardous levels over most of the fire history. An insufficient data base exists at present for extrapolation of this conclusion to analogous urban areas or very large mass fires.

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Prepared for

Office of Civil Defense, Office of the Secretary of the Army, and Defense Atomic Support Agency, Department of Defense, under OCD Work Order No. OCD-PS-65-26, Work Unit 2536A; and DASA EO 850-68

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Appendix A

PREPARATION OF TEST PLOTS FOR FIRE BEHAVIOR STUDIES USING WILDLAND FUELS TO SIMULATE URBAN CONDITIONS

Theodore G. Storey

Pacific Southwest Forest and Range Experiment Station
Forest Service, U.S. Department of Agriculture
Berkeley, California, stationed at Riverside, California

CONTENTS

Page

Introduction 2

Plot Layout 3

Estimating Fuel Volume 4

Selecting Operating Area 4

Selecting Test Sites 6

Locating Plots 6

Clearing Land 8

Conditioning the Fuel 11

Instrumentation and Burning 12

Conclusions and Recommendations 12

Recent studies in forest fire behavior by this Station have included a series of experimental fires made for the U.S. Defense Atomic Support Agency and U.S. Office of Civil Defense.[1] Piles of uprooted pinyon pine (*Pinus monophylla* Torr.& Frem.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little) were set up, dried, instrumented, and then burned at a test site along the California-Nevada border. The piles represented fuel loading and spacing of houses in residential areas of typical cities in the United States. In each plot, the piles were ignited simultaneously so as to obtain a high-intensity fire.[2]

For the proper test site, we had to have the optimum combination of large quantities of expendable, inexpensive fuels in manageable size, ease of access to the site, a long burning season, and fire-safe surroundings. And we had to have accurate fuel volume measurements of entire trees, including main stems and roots, and of stands.

In the southwestern United States, thousands of acres of pinyon pine and juniper are cleared annually.[3] Most clearings are done routinely--chiefly to convert sites from trees to grass so as to improve animal grazing and water yield. Trees are torn down by chaining, or uprooted by tractors. Brush is knocked down along with trees. Usually debris is broken and left laying, or it may be windrowed and burned. Piles or windrows are built where it is convenient. Seldom do yarding distances exceed a few hundred feet. Material is allowed to dry and then burned. Costs of these conventional types of land clearing have been published.[4]

Aerial volume tables are available for pinyon pine-juniper stands. But they are used to predict volumes of only the larger above-the-ground portions of trees, mainly as a source of charcoal and fence posts.[5] Such data were not applicable to the study reported in this paper.

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[1] Countryman, Clive M. *Mass fires and fire behavior.* U.S. Forest Serv. Res. Paper PSW-19, 53 pp., illus. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 1964.

[2] Six plots have been burned to date; Plot 760-1 on January 31, 1964; Plot 760-2 on May 15, 1964; Plot 760-3 on June 11, 1965; Plot 460-14 on December 6, 1965; Plot 460-7 on June 14, 1966; and Plot 760-12 on September 29, 1967.

[3] Cotner, Melvin L. *Controlling pinyon-juniper.* Ariz. Agr. Exp. Sta. Rep. 210, 28 pp. 1963.

[4] Cotner, Melvin L., and Jameson, Donald A. *Costs of juniper control: bulldozing vs. burning individual trees.* U.S. Forest Serv. Res. Paper RM-43, 14 pp., illus. Rocky Mountain Forest & Range Exp. Sta., Ft. Collins, Colo. 1959.

[5] Moessner, Karl E. *Preliminary aerial volume tables for pinyon-juniper stands.* U.S. Forest Serv. Res. Paper INT-69, 12 pp., illus. Intermountain Forest & Range Exp. Sta., Ogden, Utah. 1962.

In the 1964-67 experimental fires, the Station used some unique methods to select the test site, clear the land, prepare the plots, and determine the amount of fuel. By using entire trees for fuel, including roots, the cost of gathering fuel was reduced markedly. This paper describes the methods used and includes recommendations of what might be done in future work of this type.

Plot Layout

The study specified four plot sizes (5, 15, 30, and 50 acres) and two different spacings between piles (25 feet and 115 feet), each paired for a total of 16 plots. The smallest plot (5 acres) was about the size of the average block in American cities. Twenty-five feet and 115 feet represent the average close spacing and the average wide spacing, respectively, between structures in residential areas of American cities. One plot of each treatment pair was to be burned when the atmosphere became thermally stable, the other when the atmosphere was unstable. Owing to the lack of suitable terrain and tree stands, and for financial reasons, only 14 plots were actually built and one of these was smaller than planned (table 1). Fifteen single-pile plots also were built. These were used for preliminary tests of radiation measuring instruments, ignition techniques, and fuel flammability; and to determine burning characteristics of individual piles.

All piles were 46.7 feet square (1/20 acre) and contained 20 tons of burnable material on a dry weight basis. This is about the same amount of combustible fuel as in a single-story residence and garage, and covers about the same area. Piles averaged about 7 feet high. Spacings given are from edge to edge of adjacent piles and are the same on all four sides (table 2).

Table 1.--*Layout of 14 plots burned in experimental fire, Nevada, 1964-1967*

Size of Plot (Acres)	Condition of Atmosphere	Plots with piles spaced ...			
		25 ft.		115 ft.	
		No. Planned	No. Built	No. Planned	No. Built
5	stable	1	1	1	1
	unstable	1	2	1	1
15	stable	1	1	1	--
	unstable	1	[1]1	1	1
30	stable	1	1	1	--
	unstable	1	1	1	1
50	stable	1	--	1	--
	unstable	1	[2]2	1	1

[1] Piles on this plot were spaced 46.7 feet apart in a checkerboard arrangement so aisles (streets) were blocked.

[2] One plot was built 40 acres in size because not enough material was available for a 50-acre plot.

Table 2.--*Description of 14 plots built for experimental fires, Nevada 1964-1967*

Plot number	Size[1] of plot	Spacing of piles	No. of piles	Layout of piles	Pile[2] density	Total fuel weight	Fuel loading	Fuel loading
	Acres	*Ft.*		*Ft.*	*Percent*	*Tons*	*Tons/ acres*	*Lbs/ ft.*^{2}
760-2	5	25	36	6x6	42.4	840	170	8.0
760-5	5	25	28	4-1/2x6	42.4	840	170	8.0
760-15	5	25	30	5x6	42.4	840	170	8.0
760-1	5	115	9	3x3	8.33	180	33.0	1.5
760-3	5	115	9	3x3	8.33	180	33.0	1.5
760-6	15	46.7	105	([3])	42.4	2,420	170	8.0
760-13	15	25	88	8x11	42.4	2,420	170	8.0
760-4	15	115	16	4x4	8.33	500	33.0	1.5
460-7	30	25	240	15x16	42.4	5,120	170	8.0
760-10	30	25	256	16x16	42.4	5,120	170	8.0
760-8	30	115	42	6x7	8.33	980	33.0	1.5
460-14	40	25	324	18x18	42.4	6,480	170	8.0
760-12	50	25	349	19x18	42.4	8,400	170	8.0
760-11	50	115	81	9x9	8.33	1,620	33.0	1.5

[1] Some plots lack a few piles and therefore are slightly smaller in area than is indicated. This is because individual piles were built too heavy. Within limits of the cruise and clearing procedure used, all plots have the correct total fuel weight.

[2] (Area of piles ÷ area of piles and space) X 100.

[3] Checker.

Estimating Fuel Volume

A special study was conducted to develop a basis for cruising the stands for fuel volume.[6] Briefly, a representative sample of 21 pinyon pine and 16 juniper was taken from the area where the plots were to be built. Trees were measured, weighed, sampled for moisture content, and their dry weights were determined. Dry weight of the entire tree including the root was correlated statistically with tree dimensions. The closest correlation was between dry weight and maximum crown diameter, D_{CM}. This tree dimension was the basis for cruising for volume. The pinyon pine curve (fig. 1) was used for both species since the curves for pinyon pine and juniper were very similar.

Selecting Operating Area

A preliminary evaluation was made of the fuel and burning requirements in relation to fuel availability. The use of any material other than forest trees was quickly ruled out as being too expensive to purchase and transport to a safe location for burning. Other fuels considered included surplus buildings, scrap lumber, and sawmill edgings.

The choice of forest fuels was narrowed down to the pinyon pine-juniper woodlands indigenous to the high desert country of eastern California and western Nevada. In this region, pinyon pine and juniper form extensive fairly homogeneous stands in the elevational range from 5,000 feet to 8,000 feet. Extensive, flat or gently sloping areas can be found with ready access from main roads.

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[6] Storey, Theodore G. *Tree weights and fuel size distribution of pinyon pine and Utah juniper.* 1969. (See pages -32 in this volume.)

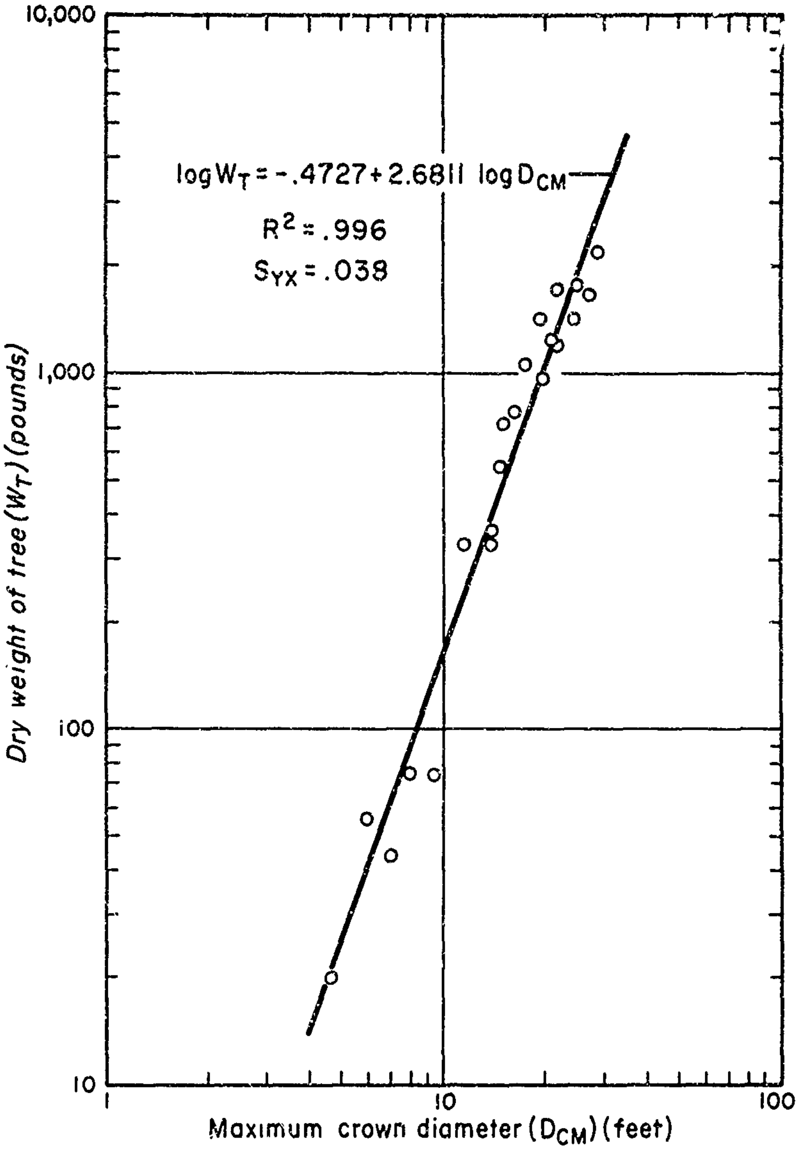

Figure 1.--*Relation between dry tree weight including the root and maximum crown diameter. Basis: 21 pinyon pines.*

Both pinyon pine and juniper are rather small trees and grow at wide spacing except on the better sites and on rocky slopes. They uproot easily because of their shallow root system and because the soil in which they grow is generally sandy and dry. Whole trees are easily handled by standard mechanical equipment without cutting them up.

Because of the dry climate, the working season and burning season in the area are quite long. Piled debris dries very quickly and, when ignited, burns intensely. Unless there is wind, however, the fire hazard in natural stands is minimal because of the sparseness and wide spacing of the vegetation. Winter snows normally are infrequent, light and dissipate rapidly, thus permitting winter burning. And the plateaus of pinyon-juniper stands are surrounded by nearly barren desert so that any accidental fires that did start would not spread far--even in the presence of wind. The area is sparsely settled and fairly remote from centers of population, but is fairly accessible by road.

The only uncertainty about choosing the California-Nevada boundary areas was the effect of nearby mountain ranges on local patterns of circulation of the air, particularly diurnal flow changes which might influence the properties of the fire plumes and ground surface wind that supplies the fuel oxidant. Because the experimental fires were planned for periods when winds are light, the possible effects of this kind were believed not to be harmful.

Selecting Test Sites

Candidate test sites within the pinyon pine-juniper type were selected on the basis of a reconnaisance survey from a light aircraft, study of aerial photos, and follow-up inspection on the ground.

Two sites were selected and designated the Basalt Site and the Mono Site. Several alternate sites with adequate volumes of fuel were rejected because of steep or broken terrain or lack of access.

The Basalt Site comprises about 45,000 acres of high desert plateau ranging in elevation from 7,000 feet to 8,000 feet above sea level. Pinyon pine is the principal tree species, with some juniper. The site lies north of U.S. Highway 6 and west of Basalt, Nevada. About half the site is administered by the U.S. Forest Service's Toiyabe National Forest and the rest by the U.S. Bureau of Land Management.

The Mono Site comprises about 15,000 acres of high desert ranging from 7,000 feet to 7,500 feet in elevation. Utah juniper is the principal tree species, with some pinyon pine. The Site is located just south of State Highway 31 along the California-Nevada border and northeast of Lee Vining, California, in California. All but a small portion of the site is on land administered by the Inyo National Forest. The remainder is Bureau of Land Management land.

Locating Plots

After the sites were selected, tree stands were tentatively matched with plot fuel requirements (table 2). The approximate fuel volume in tons per acre on each site was determined by a limited (1/2 of 1 percent) timber cruise in a representative stand in each site. Cruise technique consisted of systematically selecting 1/5-acre circular plots along one or more randomly-selected lines through the stand. From this rough estimate, the approximate acreage of tree stand needed to build each plot was determined.

This area was delineated on an aerial photograph,[7] taking into account fuel continuity, rockiness of the soil, steepness, and such other topographic features as deep gullies that transporting equipment moving the trees might not be able to negotiate. Gullies were the major obstacle. It was especially difficult to find homogeneous stands on suitable terrain large enough to provide the fuel for the 50-acre and 30-acre plots with close-spaced piles. For example, it was necessary to clear 357 acres to build Plot 760-12 on the Basalt Site, and 463 acres for Plot 460-14 on the Mono Site.

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[7] U.S. Forest Service photos (scale 1:20,000) dated June 23. 1940; and U.S. Geological Survey photos (scale 1:37,400) dated July 21, 1954 were used.

After the plot was delineated on the photo, crews walked through the area to check the actual situation. Often they had to adjust the plot boundary, shift to another plot size, or sometimes, abandon the location altogether, depending on what they found.

When a location was accepted, the area was cruised for volume by maximum crown diameter using the line plot system and a sampling intensity of 5 percent on an area basis (table 3). Crown diameters tallied during the cruise were converted to dry tree weight by means of the computed regression line for pinyon pine (fig. 1). The 5-percent sample volume then was expanded to 100 percent for the plot. The tentative plot boundary was adjusted larger or smaller depending on whether the large sample volume per acre was more or less than the small sample volume determined earlier.

The final step in plot location was to mark and map the actual location of the plot where the piles were to be built. Ideally, the plot itself was located centrally in the area to be cleared in as flat an area as possible to minimize haul distances and to facilitate piling. Frequently the plot was wholly or partially on a meadow. Meadows on both sites usually were flat, free of rocks, and easily negotiated by equipment. The medium-sized sagebrush covering the meadows crushed easily and was no hindrance to equipment.

Table 3.--*Area cruise and plot data for two test sites, Nevada and California*

BASALT SITE (pinyon pine)

Plot number	Size of plot	Number of piles[1]	Area cleared	Tons per acre[2]
	Acres		*Acres*	
760-1	5	9(9)	12.2	14.2
760-2	5	36(42)	60.8	14.5
760-3	5	9(9)	8.2	22.0
760-4	15	16(25)	35	14.2
760-5	5	28(42)	35	23.8
760-6	15	105(121)	89	27.1
760-8	30	42(49)	60	16.3
760-10	30	256(256)	269	19.0
760-11	50	81(81)	102	15.9
760-12	50	349(420)	357	23.9
760-13	15	88(121)	96	25.2
760-15	5	30(42)	49	17.2
MONO SITE (juniper)				
460-7	30	240(256)	234	21.9
460-14	40	324(324)	463	14.0
Total			1,870.2	

[1] As actually built. Figures in parenthesis are the number of piles originally planned.

[2] As cruised, including roots, dry weight basis.

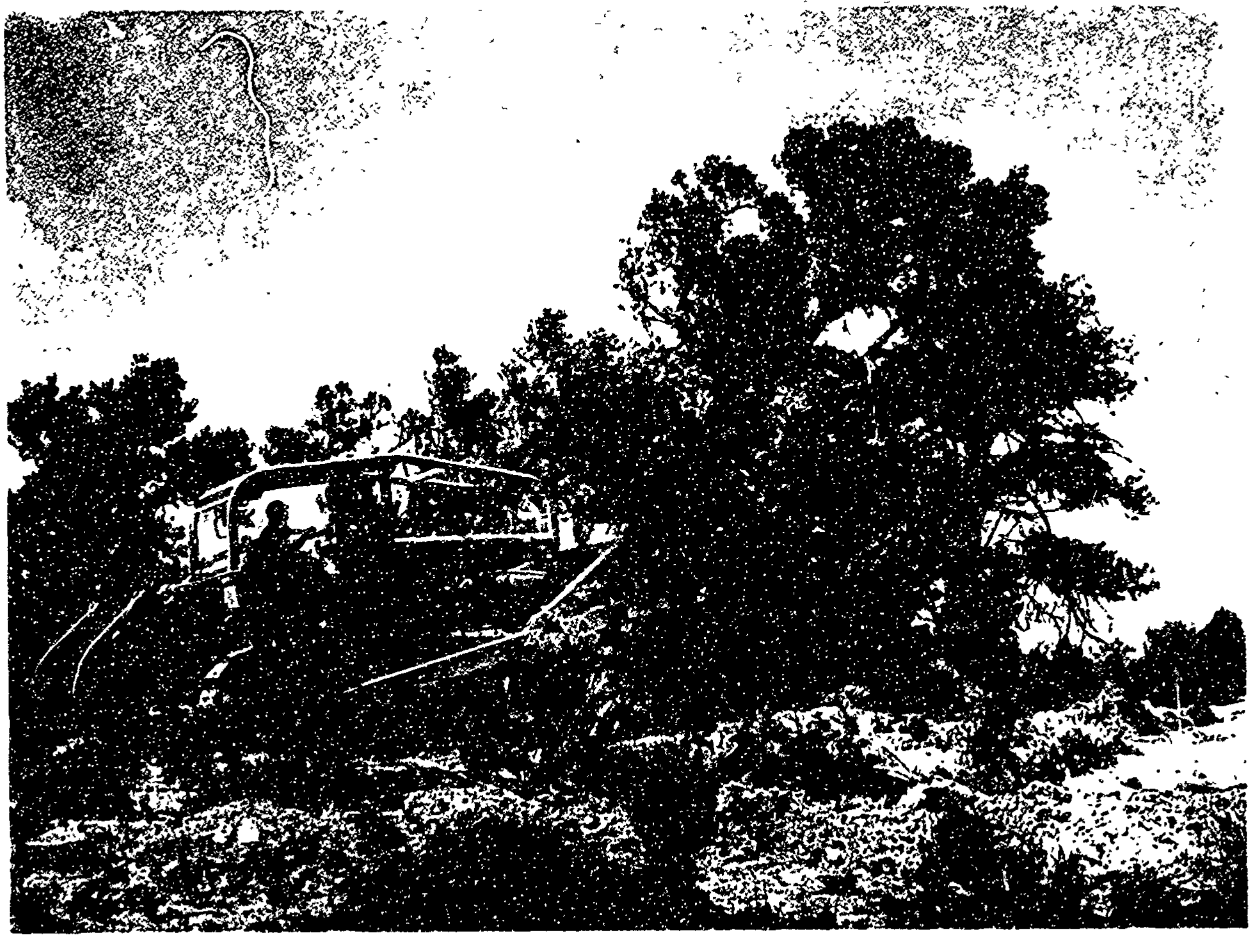

Figure 2.--*Tractor knocking down a large pinyon pine tree on the Mono Site, east of Lee Vining, California.*

Clearing Land

Trees in each of the 14 designated areas were lifted, transported, and piled to furnish the fuel for burning (fig. 2).

A private firm received a contract to do the job of plot preparation. The contract called for clearing specified areas of trees and piling them in specified arrangements at specified locations. A pilot piling study was run before letting the contract. Movies were taken of the operation and shown to prospective bidders. The job took 11 months to complete (July 1963-June 1964).

The average number and types of equipment in use at any one time consisted of the following:

Type of equipment:[1]	Number
End loader (Michigan 175A with timber forks)	2
Tractor (Allis Chalmers HD-16, and Caterpillar D-8 with blade)	2
Truck (flat bed or dump)	2

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[1] Trade names and commercial enterprises or products are mentioned solely for necessary information. No endorsement by the U.S. Department of Agriculture or the U.S. Department of Defense is implied.

These six units constituted a "team" working on one plot. Occasionally the team was divided in half to work on two plots simultaneously.

First, the contractor delineated the area to be cleared by stripping a 20-foot belt of trees completely around the perimeter. A tractor he used for this purpose made a swath two blade widths wide. Tractors equipped with straight or angled dirt blades then proceeded to uproot trees near the center where the plot was to be built and working outward toward the perimeter. Rock blades and brush blades were tried on the tractors but proved to be less efficient than the dirt blades. To minimize loss of material the contractor was required not to knock trees down more than ten days in advance of piling. Because needles, twigs, and small branches dried rapidly in the arid climate and would either shatter or break off in handling, we required the contractor to pile all material within 10 days after the trees were lifted out of the ground.

On the Basalt Site, the contractor experimented with cabling (mowing) down the trees but soon reverted to uprooting with tractors. He found that cabling tied up two tractors and reduced their flexibility of use. Frequently they were needed on short notice to bunch or pile in order to keep up with the end loaders and haul trucks. They had to unhook from the cable for this use and rehook when they were through. This procedure proved prohibitively time consuming.

Usually the tractor took two passes to uproot a tree. Its first pass, made with the blade raised about 3-1/2 feet, would knock the tree over and free most of the roots. Its second pass, made with the bottom of the blade at ground level, would lift the roots free of the soil. In the clearing process the tractors bunched the trees randomly in the area to facilitate picking up by the end loaders (fig. 3). The tractor operators became very skilled in the technique of arranging the trees properly and making the bunches the proper size for one bite by the loaders. The loaders were powerful enough to lift and carry at one time two or three large trees, each weighing perhaps 3,000 pounds.

As soon as a few acres were knocked down, the inspector and his assistant would survey and stake the plot perimeter and the corners of the first few piles. This work was done with compass and chain. Because of the congestion of heavy equipment in the pile area, it was not feasible to stake more than a few piles ahead of actual piling for staking would be obliterated and have to be redone.

The first few piles on a plot were built directly by the tractors as they knocked the trees down. Trees were pushed along the ground to the piles. This work continued until pushing distances exceeded about 300 feet, depending on the terrain and rockiness of the soil.

Beyond 300 feet, trees were lifted and carried to the piles in two ways by the loaders or by trucks of several types (fig. 4).

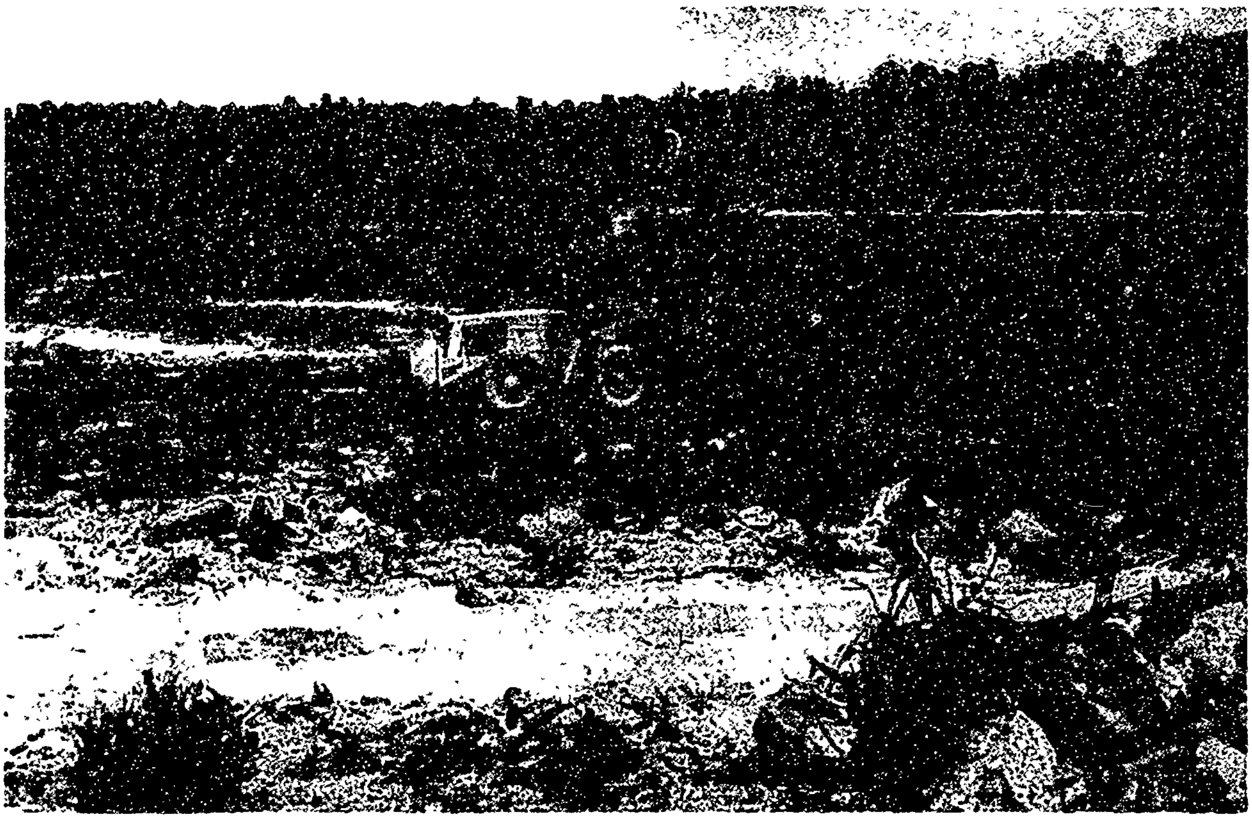

Figure 3.--*End loader with timber forks transports a bunch of pinyon pine trees to a pile on Plot 760-1, on the Basalt Site west of Basalt, Nevada. The area was rockier than average. The volcanic rocks were very abrasive.*

Figure 4.--*Haul truck with specially built bed empties load of pinyon pine trees. The power-drive backboard slid from left to right, scraping the trees off the rear of the truck. Dump trucks and plain flat-bed trucks also were used to haul trees.*

The advantages of using trucks were that they could carry more than the loaders and were much cheaper to operate. However, the road speed of the trucks was slightly less than that of the loaders, they were less maneuverable, and they could not negotiate the frequently soft, rocky, and steep terrain off the haul roads.

The usual procedure was for the trucks to dump their load near a pile and for the loaders to dump directly on the pile. A tractor then would push the trucked material into the staked area and square it into shape with the blade. On occasion the loaders were used to build piles directly, to supplement material in piles, and to square them up.

A judgment-and-survey method was used to estimate when a pile contained the desired 20 tons of material dry weight. The small plots built first involved clearing only a few acres. The equipment operators and inspector, working together, would ocularly divide the down timber on the area to be cleared into the same number of portions as there were piles on the plot. Each portion was then cleared and placed on a pile. The equipment operators quickly became proficient in estimating ocularly the proper amount of material for a pile. Periodic checks were made by surveying the area cleared and comparing the percent of area cleared with percent of piles built. Adjustments were made as necessary. One difficulty encountered using this procedure was judging compaction. Certain operators using the same equipment tended to compact the fuel more than others and certain types of equipment compacted the fuel more than other types when operated by the same person. Some plots actually ended up short a few piles (table 3). This was probably the result of some piles being overloaded and also to limits of accuracy of the timber cruise.

Counting trees was another method explored to obtain the prescribed amount of fuel in a pile. Using the average number of trees needed per pile as calculated from the cruise data, the field supervisor and crew using tally whackers, merely counted the designated number of trees into each pile as the equipment brought them in from the area. This procedure was soon abandoned. It took too much of the supervisory personnel's and equipment operator's time. Furthermore, the amount of fuel per pile varied too widely largely because of differences in tree sizes that occurred in the stands.

Conditioning the Fuel

The plots scheduled to be burned first were completed first so as to allow ample time for drying. The study plan specified that the plots will be burned when their average moisture content approximates that of wood in buildings. Buildings average about 15 percent moisture content on a dry weight basis whereas freshly piled pine and juniper debris average 85 percent or more. A drying study of freshly-piled debris of these two species was conducted concurrently to determine how soon the material would be dry enough to start the burning tests. Moisture content was sampled periodically by size class. We found that the desired moisture content would be reached in about 6 months--depending on the season of the year. This rapid drying is attributable to the dry desert climate, high elevation, and to the fact that needles remained on the branches and continued to transpire moisture. The rate of drying the first few weeks was found to be vary rapid tapering off over succeeding weeks. This drying trend is characteristic of all cellulose material.

The plots that have been burned to date, 760-1, 760-3, 760-2, 460-14, 460-7, and 760-12 dried for 7 months, 11 months, 12 months, 18 months, 27 months, and 45 months respectively, before burning.

Instrumentation and Burning

Before burning, each plot was heavily instrumented to measure characteristics of the fire and its environment.[8,9] Field instrumentation of even a small plot had to be started several months before burning. Instrumentation and procedures will vary considerably from burn to burn. And details are given in the Test Plan written for each individual burn.

Conclusions and Recommendations

1. Experience to date in preparing, conditioning, and burning experimental fires utilizing pinyon-juniper debris has been favorable. In 1963 construction of two small fire test plots was started on a portion of the area burned by the Volcano Fire of 1960, near Auburn, California. The large trees up to 4 feet in diameter and 150 feet long were difficult to knock down, yard, and pile. Deep winter snows delayed plot construction. Cost per ton was nearly twice that in the Basalt and Mono test sites.

Pinyon-juniper debris dried rapidly, permitting early burning. Weather conditions were no particular problem in the field work of plot preparation. The fuel proved to be relatively durable when properly handled. Needles, twigs, and smaller branches did not shatter or break off when trees were moved and piled within 10 days of being uprooted. Piled material proved to be fairly resistant to weathering. Winter snows up to 12 inches deep, strong winds, and sand storms were some of the conditions encountered.

Even larger areas of pinyon pine-juniper stands can be found in eastern Nevada and in Arizona. Large portions of this are cleared each year as a land management practice to improve grazing and water yield. Cooperative arrangements probably could be worked out to use the material removed for test plots.

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[8] Countryman, *op. cit.*

[9] Philpot, C.W. *Temperatures in a large natural-fuel fire.* U.S. Forest Serv. Res. Note PSW-90, 14 pp., illus. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 1965.

2. Some difficulty was encountered in writing the clearing contract and communicating with prospective bidders so as to get the results wanted. Both Forest Service and contractor experience to date has been with routine clearing of pinyon and juniper for site conversion. In this type of work the debris can be piled wherever is convenient. For the test, debris had to be concentrated into precise volumes and arranged precisely. Haul distances would be much greater than usual. We had difficulty in getting these two points across to the contractors bidding on the job. Their lack of understanding was reflected in generally unrealistic low bids. The contractor that was awarded the job encountered financial problems, although he managed to complete the job.

In future work of this type extreme care should be taken in writing the contract requirements so that they are unambiguous. Prospective bidders should be carefully and thoroughly oriented, and the contractor selected should be very closely supervised in his work.

We suggest that one or more pilot test plots be built before calling for bids to get an estimate of the costs of the big job. Experience to date also should be helpful for estimating costs of future work.

3. The existing tree weight-crown diameter relationships for pinyon pine and Utah juniper may be directly applicable to these and to other species of pinyon pine and juniper growing elsewhere in the Southwest. It is recommended, however, that this be checked. This can be done by analyzing a representative sample of trees from the new sites and plotting the resultant data points on the existing regression lines. If the trend of the new points appears to be greatly different from the regression, more trees should be sampled and new regressions computed and used.

4. Good aerial photos are essential for selecting sites and prospective plot areas. Photos of pinyon pine-juniper stands, however, can be as much as 5 years old or more because both species grow very slowly. The stand will change very little in appearance in this period. For future studies, particularly if larger areas are involved, it would be well to consider taking special aerial pictures tailored to study requirements. Larger scale photos should permit stereo mapping and cruising to reduce over-all costs.

5. The technique of clearing and the individual types of equipment and equipment teams developed and used by the contractor appeared to be equal to the job. The debris was bunched by tractors and then picked up by end loaders. The end loaders proved ideal for loading, carrying short distances, and piling. Trucks appeared to be the most efficient in medium and long hauls. The contractor's biggest problems were in maintaining equipment and in keeping competent operators. Haul trucks often broke down because they were old and not built to stand severe service. The tractors and loaders were nearly new at the start of the job and they stood up very well. Only near the end of the job did they

start to develop serious maintenance problems. Strict equipment specifications should be listed in the bid and the equipment should be inspected by a competent equipment mechanic before a particular bid is accepted. The large, hard, rough volcanic rocks found on both sites were very hard on tires, tracks, and structural members of the equipment.

Appendix B

TREE WEIGHTS AND FUEL SIZE DISTRIBUTION OF PINYON PINE AND UTAH JUNIPER

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CONTENTS

Page

Introduction.. 16

Study Location.. 17

Study Methods.. 17

  Tree, Crown, and Root Weights...................... 18

  Fuel Size Distribution............................. 23

Results and Discussion................................ 26

  Total Weight and Maximum Size...................... 26

  Distribution of Fuel Weight........................ 27

  Similarity Among Branches.......................... 29

Conclusions... 30

Literature Cited...................................... 31

In experimental fires conducted by this Station for the U.S. Defense Atomic Support Agency and the U.S. Office of Civil Defense, the fuel used consisted of uprooted trees. Piles of single-leaf pinyon pine (*Pinus monophylla* Torr. and Frem.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little) were arranged to simulate the spacing and weight of fuel in individual houses and residential areas (Countryman 1964). The piles in the test plots were dried, and then ignited simultaneously so as to obtain a high-intensity fire. To aid in timber cruising for plot preparation and in interpretation of fire behavior, we gathered information on fuel weight and size distribution.

This paper describes how pinyon pine and Utah juniper trees were selected and sampled at the test sites, the analytical procedures used, and the results obtained in relating weight of fuel to size and to dimensions, and in determining distribution of fuel weight.

Most investigators agree that geometry of a fuel particle, including its shape and size, influences the start, spread, and behavior of fire. Fons (1946) found that differences in particle geometry of natural forest fuels accounted for differences in ignition times and burning rates. He used surface-to-volume ratio to quantify the variations in fuel particles. In later work, Fons et al. (1960) built cribs using wood sticks of different dimensions but constant spacing. They ignited cribs at one end and measured rate of fire spread. Everything else being equal, the finer the fuels the more quickly fire spread. The effect decreased rapidly at stick sizes greater than 3/4 inch.

For many tree species, the dry weight of foliage, dry weight of branchwood, and the two combined are closely related to stem and crown dimensions.[1] But studies made so far have not considered the volume of fuel in the main stem or in roots. Nor were branches analyzed by size classes. Attiwill (1962) reported that dry weight of all materials above any given point on a eucalyptus branch is closely related to the girth of the branch at that point.

Moessner (1962) developed volume tables for pinyon pine and juniper to estimate the quantity of usable wood products. The products included volume of charcoal produced from pinyon pine and number of fence posts obtainable from Utah juniper stems. But no data were available on weight of entire trees, including roots, of these species. We used roots in the present study because both species uprooted readily, thereby reducing the cost of gathering fuel.

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[1] Brown 1965; Fahnestock 1960; Kittredge 1944; Rothacher et al. 1954; Storey et al. 1955; Storey and Pong 1957; Tufts 1919; Wendel 1960.

Study Location

The study area is representative of about 2,500 square miles of pinyon pine-juniper woodland straddling the California-Nevada border, east and southeast of Lee Vining, California. Elevations ranged from 6,500 feet to 8,000 feet. Topography is rolling to flat, interspersed with dry washes of varying widths. Sides of the draws often are steep and rocky and covered with dense stands of pinyon pine and juniper. Both species also grow on moderate slopes, plateaus, and bottoms of draws. More often the bottoms of the draws are covered with nearly pure stands of sagebrush, big sagebrush (*Artemesia tridentata*) and black sagebrush (*Artemesia nova*).

Sample pinyon pine trees were selected from three sites in the study area: Pizona, Basalt No. 1, and Basalt No. 2. Utah junipers were selected from two sites: Basalt No. 1 and Mono.

The Pizona Site lies on the Inyo National Forest, Mono County, California, about 1/2 mile from the Nevada border at an elevation of 6,700 feet. Of volcanic origin, the soil is light sandy loam, with medium to large size volcanic rocks underlain by hardpan. Nearlv pure stands of pinyon pine grow there. Specimens P-1 to 5 were sampled there.

The Basalt Site No. 1 is 8-1/2 miles from the California border, in Mineral County, Nevada. It resembles the Pizona site, except the draw is wider and elevation is 7,000 feet. The land is under the jurisdiction of the U.S. Bureau of Land Management. Junipers cover about 10 percent of the area. Specimens P-6 to 16 and J-13 and 14 were selected here.

The Basalt Site No. 2, also in Mineral County, Nevada, lies within the Toiyabe National Forest, 2 miles west of Basalt Site No. 1, at 7,500 feet elevation. Junipers grow on about 15 percent of the land. Pinyon pines P-17 to 31 were sampled here.

The Mono Site, in Mono County, California, lies about 25 miles northwest of Basalt Site No. 1, at 7,100 feet elevation. The soil is coarse, sandy, and volcanic, with few rocks underlain by hardpan at depths of several feet. Pinyon pine covers about a third of the area. From here, we selected specimens J-1 to 12 and J-15 to 17 for sampling.

Study Methods

Pinyon pine is characteristically a short, bushy, many-branched, rather gnarled tree. When young, it usually has a single central stem, but as it grows older the degree of branching increases. Live branches persist from top to near the ground throughout its life. Often it may have two or more main stems joining at the ground line. But more often the first branches start from a single trunk at about 1 foot above ground.

Utah juniper, in the study area, is characteristically a large sprawling bush. Only rarely will even a young tree have one central stem and grow like a conventional tree. It appeared that the underground parts spread in some manner, and that sprouts arose from them to form more trunks, but Utah juniper is generally regarded as a non-sprouter (Arnold et al. 1964) or this characteristic is reported as unknown (Sampson and Jesperson 1963).

On most sites we stratified trees into four broad stem-diameter or crown-diameter classes to cover the range in tree sizes found. Trees were chosen at random from each diameter class in proportion to the frequency of trees in the class. The trees sampled appeared to be representative of trees in the stands as to range in size, form, and dominance.

The sample included 31 pinyon pines with stem diameters from 2.5 to 23 inches at 1 foot above ground, and 17 Utah junipers with average crown diameters from 4.6 to 32.4 feet (*table 1*).

Tree, Crown, and Root Weights

Each sample tree was photographed and measured for height, maximum crown diameter, and average crown diameter (average of the widest and narrowest dimensions) on the standing tree. Height was measured with an Abney level for tall trees and with a steel tape for short trees. The height measurement was checked after the tree was uprooted.

Crown diameters were measured with a steel tape by two men standing on the ground. Measurement locations usually were within arms reach.

Stem diameter 1 foot above ground and stem diameter breast high were measured for trees having single trunks.

After trees were measured, they were uprooted by a tractor equipped with an angled dirt blade. The operator was instructed to remove the trees so as to obtain the maximum amount of root material. Soil and rocks adhering to the roots were removed, and all but the largest trees were weighed intact. Large trees were cut up into convenient portions and weighed separately. Next, the root was cut from the stem or stems at the former ground line and the tree reweighed.

Trees were weighed by means of a ring dynamometer coupled into the lifting cable on a boom truck. The largest pinyon pine weighed 3,743 pounds green weight and the largest juniper, 4,248 pounds. Representative samples of foliage, branchwood, stems, and roots were taken from each tree and distilled in xylene to determine their moisture content (Buck 1939). Moisture contents were applied to convert the green weights of crown and root to ovendry weights.

Table 1.--*Physical characteristics of sample trees, by site and tree number*

Sampling site and tree number	Tree height (H_T)	Stem diameter at 1 foot (D_{S1})	Crown diameter		Dry weight		
			Maximum (D_{CM})	Average[1] (D_{CA})	Tree (W_T)	Crown (W_C)	Root (W_R)
	Feet	*Inches*	*Feet*	*Feet*	——— *Pounds* ———		
			PINYON PINE				
Pizona:							
P-1	5.5	2.5	3.8	3.8	--	10.0	--
P-2	10.6	7.3	10.9	10.7	--	128.0	--
P-3	14.1	9.1	12.5	12.0	--	184.0	--
P-4	16.6	10.1	16.1	13.8	--	402.0	--
P-5	33.5	20.4	25.1	22.5	--	1,814.0	--
Basalt No. 1:							
P-6	6.7	4.1	6.9	6.7	44.0	35.0	9.0
P-7	6.9	3.2	4.7	4.1	20.0	17.0	3.0
P-8	13.9	7.0	11.4	10.6	327.0	202.0	125.0
P-9	15.6	11.4	14.0	12.9	355.0	317.0	38.0
P-10	17.0	14.6	15.2	14.0	719.0	610.0	109.0
P-11	18.0	13.6	14.8	12.3	547.0	488.0	59.0
P-12	18.7	10.1	13.8	13.8	327.0	282.0	45.0
P-13	19.4	14.7	17.7	15.0	1,057.0	905.0	152.0
P-14	19.6	18.1	24.3	20.4	1,411.0	1,243.0	168.0
P-15	24.0	17.4	22.2	20.2	1,727.0	1,395.0	332.0
P-16	10.3	6.0	8.0	7.7	75.1	66.5	8.6
Basalt No. 2:							
P-17	10.5	6.0	9.0	8.9	74.9	62.2	12.7
P-18	17.5	17.0	20.0	17.5	976.0	814.0	162.0
P-19	18.5	14.0	16.5	16.0	767.0	673.0	94.0
P-20	20.0	16.0	22.0	22.0	1.203.0	1,038.0	165.0
P-21	20.5	20.0	29.0	25.0	2,164.0	1,822.0	342.0
P-22	23.0	23.0	27.5	23.8	1,630.0	1,344.0	286.0
P-23	24.0	18.0	21.0	20.2	1,214.0	1.023.0	191.0
P-24	26.0	20.0	19.5	16.2	1,441.0	1,247.0	194.0
P-25	30.0	20.0	25.0	22.5	1,766.0	1,548.0	218.0
P-26	9.4	6.0	6.0	5.4	55.3	47.7	7.6
P-27	18.0	18.0	20.0	--	--	[2]21.9	--
P-28	30.0	18.0	22.0	--	--	[2]30.4	--
P-29	22.0	16.0	22.0	--	--	[2]21.8	--
P-30	28.0	11.0	12.0	--	--	[2]26.1	--
P-31	40.0	15.0	15.0	--	--	[2]16.6	--
			UTAH JUNIPER				
Mono:							
J-1	5.5	(3)	13.3	13.2	226.0	158.0	68.0
J-2	8.5	(3)	10.1	9.4	117.0	217.0	100.0
J-3	9.0	(3)	10.8	9.4	144.0	87.9	56.0
J-4	9.0	(3)	11.1	10.6	241.0	160.0	81.0
J-5	10.5	(3)	12.6	12.4	298.0	200.0	98.0
J-6	11.5	(3)	22.3	22.2	1,154.0	1,006.0	148.0
J-7	13.0	(3)	24.0	22.3	1,221.0	1,011.0	210.0
J-8	13.0	(3)	22.7	17.9	1,006.0	799.0	227.0
J-9	14.0	(3)	28.1	23.2	2,250.0	1,912.0	338.0
J-10	15.0	(3)	28.8	25.4	1,854.0	1,474.0	380.0
J-11	20.0	(3)	32.6	28.6	2,826.0	2,418.0	408.0
J-12	33.0	(3)	33.0	32.4	2,883.0	2,266.0	617.0
Basalt No. 1:							
J-13	6.5	(3)	4.8	4.6	56.0	44.0	12.0
J-14	14.2	(3)	12.8	12.5	468.0	382.0	86.0
Mono:							
J-15	7.5	6.0	6.0	6.0	--	63.0	--
J-16	13.5	(3,4)	20.0	18.5	--	656.0	--
J-17	12.0	(3,4)	19.0	17.5	--	[2]9.4	--

[1] Average of widest and narrowest crown dimensions as measured from ground.

[2] One randomly selected 4-inch diameter limb only.

[3] Trees with multiple stems.

[4] Diameter of largest stem about 10 inches.

Table 2.--*Regression equations and error terms for estimating dry tree weight of pinyon pine from crown and tree dimensions (basis: 21 trees)*

Equations	R^2[1/]	S_{yx}[2]	Confidence limits[3]	
			Stands[4] of trees	Individual trees
			Percent[5]	
$\log W_T = -.4727 + 2.6811 \log D_{CM}$	0.996	0.038	+ 2.0 - 1.9	+ 19.2 - 16.1
$\log W_T = -.4038 + 2.7164 \log D_{CA}$	.938	.157	+ 8.2 - 7.6	+ 106.2 - 51.5
$\log W_T = -1.2826 + 3.2549 \log H_T$	.912	.188	+ 9.9 - 9.0	+ 137.9 - 58.0
$\log W_T = -.0922 + 2.4116 \log D_{S1}$	.956	.133	+ 6.9 - 6.5	+ 84.5 - 45.8

[1] Coefficient of determination.

[2] Standard error of estimate.

[3] At 95 percent level for mean values of crown and tree dimensions. Limit above regression line is larger than below line because equation is logarithmic.

[4] For stands or groups of trees with weights about same as sample.

[5] Of W_T predicted by equation.

Analysis procedures followed Wendel's (1960) except that maximum crown diameter, average crown diameter, tree height, and stem diameter 1 foot above ground instead of stem diameter breast high were used as independent variables. Measurement of diameter breast high was not feasible because both species branched extensively below this height.

In pinyon pine dead branchlets and the full-length crown often obscured the stem at the 1-foot height. Nor would stem diameter at any level be practical for cruising the many-branched juniper trees. The most feasible measurements appeared to be crown diameter and total tree height.

Pinyon pine.—A process of data plotting and curve-fitting indicated that tree weight, W_T, of pinyon pine was correlated with each of the four independent variables: maximum crown diameter, D_{CM}, average crown diameter, D_{CA}, tree height, H_T, and stem diameter at 1 foot, D_{S1}. A double logarithmic relationship gave the best fit to the data. Regression equations were computed for each of the four relationships and the coefficient of determination and standard error of estimate for each were calculated (*Table 2*).

A similar curve form was found to apply for estimating ovendry crown weight, W_C, and ovendry root weight, W_R, from each of the same four variables (*tables 3,4*). A regression equation also was computed for ovendry root weight, W_R, on ovendry tree weight, W_T:

$$W_R = 1.70 + .15\ W_T.$$

The coefficient of determination (R^2) was .90 and the standard error of estimate 34.1 pounds on an average W_R of 130 pounds.

Table 3.--*Regression equations and error terms for estimating dry crown weight of pinyon pine from crown and tree dimensions (basis: 26 trees)*

Equations	R^2[1]	S_{yx}[2]	Confidence limits[3]	
			Stands[4] of trees	Individual trees
			Percent[5]	
$\log W_C = -.6111 + 2.7294 \log D_{CM}$	0.970	0.117	+ 5.4 − 5.2	+ 71.6 − 41.7
$\log W_C = -.5954 + 2.8090 \log D_{CA}$	.948	.155	+ 7.3 − 6.7	+ 104.2 − 51.0
$\log W_C = -1.2862 + 3.1854 \log H_T$	.928	.182	+ 8.6 − 7.9	+ 131.3 − 56.8
$\log W_C = -.0086 + 2.4478 \log D_{S1}$	.973	.112	+ 5.2 − 4.9	+ 67.6 − 40.3

[1] Coefficient of determination.

[2] Standard error of estimate.

[3] At 95 percent level for mean values of crown and tree dimensions. Limit above regression line is larger than below line because equation is logarithmic.

[4] For stands or groups of trees with weights about same as sample.

[5] Of W_C predicted by equation.

Table 4.--*Regression equations and error terms for estimating dry root weight of pinyon pine from crown and tree dimensions (basis: 26 trees)*

Equations	R^2[1]	S_{yx}[2]	Confidence limits[3]	
			Stands[4] of trees	Individual trees
			Percent[5]	
$\log W_R = -1.2314 + 2.6256 \log D_{CM}$	0.920	0.180	+ 9.5 − 8.6	+ 129.0 − 56.4
$\log W_R = -1.1736 + 2.6688 \log D_{CA}$	.901	.200	+10.5 − 9.6	+ 151.0 − 60.2
$\log W_R = -1.9662 + 3.1396 \log H_T$	.843	.252	+13.5 −11.9	+ 218.0 − 68.6
$\log W_R = -.6161 + 2.3036 \log D_{S1}$	.868	.231	+13.5 −12.8	+ 190.0 − 65.5

[1] Coefficient of determination.

[2] Standard error of estimate.

[3] At 95 percent level for mean values of crown and tree dimensions. Limit above regression line is larger than below line because equation is logarithmic.

[4] For stands or groups of trees with weights about same as sample.

[5] Of W_R predicted by equation.

Utah juniper.—Essentially the same type of analysis used for pinyon pine was applied to Utah juniper with similar results. We computed regression equations and error terms for dry tree weight of juniper as a function of each of three independent variables: maximum crown diameter, D_{CM}, average crown diameter, D_{CA}, and tree height, H_T, (*table 5*). A similar curve form was found to apply for estimating ovendry crown weight and ovendry root weight of juniper from each of the three variables (*tables 6,7*). A regression equation also was computed for ovendry root

Table 5.--*Regression equations and error terms for estimating dry tree weight of Utah juniper from crown and tree dimensions (basis: 14 trees)*

Equations	R^2[1]	S_{yx}[2]	Confidence limits[3]	
			Stands[4] of trees	Individual trees
			Percent[5]	
$\log W_T = 0.0233 + 2.2320 \log D_{CM}$	0.954	0.126	+ 8.1	+ 78.5
			− 7.4	− 44.0
$\log W_T = .0108 + 2.3083 \log D_{CA}$	.945	.137	+ 8.8	+ 88.1
			− 8.1	− 46.8
$\log W_T = .1998 + 2.3835 \log H_T$	.702	.319	+21.7	+ 333.0
			−17.8	− 77.0

[1] Coefficient of determination.

[2] Standard error of estimate.

[3] At 95 percent level for mean values of crown and tree dimensions. Limit above regression line is larger than below line because equation is logarithmic.

[4] For stands or groups of trees with weights about same as sample.

[5] Of W_T predicted by equation.

Table 6.--*Regression equations and error terms for estimating dry crown weight of Utah juniper from crown and tree dimensions (basis: 16 trees)*

Equations	R^2[1]	S_{yx}[2]	Confidence limits[3]	
			Stands[4] of trees	Individual trees
			Percent[5]	
$\log W_C = 0.0201 + 2.1664 \log D_{CM}$	0.940	0.144	+ 7.4	+ 94.4
			− 6.9	− 48.6
$\log W_C = -.1441 + 2.3678 \log D_{CA}$	.934	.152	+ 9.3	+ 101.5
			− 8.5	− 50.4
$\log W_C = .0631 + 2.5248 \log H_T$	.871	.281	+18.4	+ 265.0
			−15.6	− 72.6

[1] Coefficient of determination.

[2] Standard error of estimate.

[3] At 95 percent level for mean values of crown and tree dimensions. Limit above regression line is larger than below line because equation is logarithmic.

[4] For stands or groups of trees with weights about same as sample.

[5] Of W_C predicted by equation.

weight, W_R, on ovendry tree weight, W_T:

$$W_R = 31.46 + .16\ W_T.$$

The coefficient of determination (R^2) was .95 and the standard error of estimate 56 pounds on an average W_R of 202 pounds.

Fuel Size Distribution

Pinyon pine.—One of the smaller pinyon pines (P-26) was analyzed by successively stripping the needles and clipping or cutting the twigs, branches, stem, and roots into several size classes (*table 8*).

Table 7.--*Regression equations and error terms for estimating dry root weight of Utah juniper from crown and tree dimensions (basis: 14 trees)*

Equations	R^2[1]	S_{yx}[2]	Confidence limits[3]	
			Stands[4] of trees	Individual trees
			Percent[5]	
$\log W_R = -0.0141 + 1.7553 \log D_{CM}$	0.935	0.118	+75.0 − 7.0	+ 72.0 − 43.0
$\log W_R = .8714 + 1.0122 \log D_{CA}$	.469	.338	+23.0 −19.0	+ 374.0 − 79.0
$\log W_R = .1188 + 1.8799 \log H_T$	.692	.257	+17.1 −14.7	+ 227.0 − 64.1

[1] Coefficient of determination.

[2] Standard error of estimate.

[3] At 95 percent level for mean values of crown and tree dimensions. Limit above regression line is larger than below line because equation is logarithmic.

[4] For stands or groups of trees with weights about the same as sample.

[5] Of W_R predicted by equation.

Table 8.--*Distribution of dry weight in the crown, roots, and entire tree of a 6-inch diameter pinyon pine (P-26)*

Size class (inches)	Crown		Roots[1]		Tree	
	Dry weight	Distribution	Dry weight	Distribution	Dry weight	Distribution
	Pounds	*Percent*	*Pounds*	*Percent*	*Pounds*	*Percent*
Needles	14.6	30.6	--	--	14.6	26.4
< 1/4	8.7	18.2	0.2	3.0	8.9	16.1
1/4-1/2	3.0	6.3	1.0	12.4	4.0	7.2
1/2-1	4.0	8.4	1.9	25.0	5.9	10.7
1-2	3.5	7.3	.9	12.1	4.4	8.0
2-4	5.9	12.4	3.6	47.5	17.5	31.6
4-6	8.0	16.8				
Total	47.7	100.0	7.6	100.0	55.3	100.0

[1] Roots comprise 13.7 percent of tree on dry weight basis.

A representative fuel moisture sample of the material in each size class was taken at the time the material was weighed. These samples were later analyzed by xylene distillation (Buck 1939) or by ovendrying, using standard procedure, and moisture content was determined. Moisture contents obtained were applied to convert green weights of the material to ovendry weights.

Tree P-26 was the only pinyon to be cut up completely, but portions of five other larger pinyons from 11 inches to 18 inches in diameter were analyzed. We cut up one randomly selected 4-inch diameter branch from each tree (*table 9*). Our purpose was twofold: (a) to explore the feasibility of using a sample branch or branches to reduce the work of future size analyses, and (b) to compare the fuel size distribution of branches with that of the crown of a small tree of the same girth. A sample branch as a "typical weight unit" has been used successfully for Utah juniper by Mason and Hutchings (1967).

Utah juniper.—A small juniper (J-15) received the same treatment as a small pinyon except that the root was not included in the analysis (*table 10*).

Fuel size distribution in a large juniper (J-16) was determined by cutting up, stripping, and analyzing representative branches and stems and expanding these data to the entire tree (*table 10*). The tree consisted of several stems close to each other, each about 10 inches in diameter. One stem was chosen at random for more complete analysis. All branches on this stem measuring 4 inches in diameter or larger were cut at 4 inches. Two branches were selected at random from among these for complete analysis.

Table 9.--*Distribution of dry weight in the crowns of Utah juniper and pinyon pine*

Size class (inches)	Utah juniper			Pinyon pine tree P-26
	Tree J-15	Tree J-16		
		Whole crown	Upper crown[1]	
	Percent			
Needles	45.9	26.8	30.5	30.6
< 1/4	9.8	6.7	7.6	18.2
1/4-1/2	4.4	5.0	5.7	6.3
1/2-1	6.7	5.6	6.4	8.4
1-2	7.8	9.6	10.9	7.3
2-4	9.5	19.8	22.5	12.4
4-6	15.9	14.5	16.4	16.8
6-10	--	4.4	--	--
10	--	7.6	--	--
Total	100.0	100.0	100.0	100.0
	Pounds	*Pounds*	*Pounds*	*Pounds*
Dry weight	63.0	652.3	573.7	47.7

[1] All material less than 6 inches in diameter, for purposes of comparison with juniper J-15 and pinyon P-26.

The two sample branches were cut up and analyzed the same way as the small trees (*table 11*). Next, all of the remaining 4-inch branches on the stem were weighed as a group. Total dry weight was computed and distributed among the various size classes on the basis of the analysis of the two branches. The remaining material from the sample stem larger than 4 inches was cut and weighed by size class. Green weights were converted to dry weights using standard procedures.

Table 10.--*Comparative distribution of dry weight among representative 4-inch diameter branches and a portion of the crown of pinyon pine*

Size class (inches)	Distribution of dry weight						
	Tree P-26 upper crown[1]	Tree P-27 branch	Tree P-28 branch	Tree P-29 branch	Tree P-30 branch	Tree P-31 branch	Average (trees P-27 to P-31)
	Percent						
Needles	36.7	23.6	24.3	18.3	27.6	23.6	23.6
< 1/4	21.9	14.6	11.5	13.6	10.2	13.2	12.6
1/4-1/2	7.6	5.7	7.5	5.2	4.6	7.6	6.1
1/2-1	10.1	10.5	7.5	8.6	7.5	9.1	8.6
1-2	8.8	[2]32.3	[2]20.1	[2]26.0	[2]29.4	[2]24.9	[2]26.5
2-4	14.9	[3]13.3	[3]29.1	[3]28.3	[3]20.7	[3]21.7	[3]22.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
Dry weight	39.7	21.9	30.4	21.8	26.1	16.6	23.4

[1] All material less than 4 inches in diameter for purposes of comparison with branches of trees P-27 to P-31.

[2] 1- to 3-inch size class.

[3] 3- to 4-inch size class.

Table 11.--*Comparative distribution of dry weight among representative 4-inch diameter branches and a portion of the crown of Utah juniper*

Size class (inches)	Distribution of dry weight				
	Tree J-16		Tree J-17 branch	Average (Trees J-16 and J-17)	Tree J-15 upper crown[1]
	Branch 1	Branch 2			
	Percent				
Needles	41.0	35.3	39.5	38.6	54.5
< 1/4	12.0	6.9	10.8	9.9	11.7
1/4-1/2	2.0	10.4	1.8	4.7	5.3
1/2-1	8.0	7.0	6.7	7.3	7.9
1-2	12.0	13.5	23.7	16.4	9.2
2-4	25.0	26.9	17.5	23.1	11.4
Total	100.0	100.0	100.0	100.0	100.0
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*
Dry weight	8.0	9.6	9.4	9.0	53.0

[1] All material less than 4-inches diameter, for purposes of comparison with branches of junipers J-16 and J-17.

The remaining 10-inch stems were cut up into size classes 4 inches or smaller, 4 to 6 inches, and 6 to 10 inches. Dry weights were computed. Total weight of the 4-inch branches was distributed among the standard size classes, 2 to 4 inches or smaller, based on results of the complete analysis of the two branches mentioned above.

Another large juniper, J-17, was only partially analyzed. One 4-inch diameter branch was selected at random from all of the 4-inch diameter branches on the tree and then cut up (*table 11*).

Results and Discussion

Total Weight and Maximum Size

Pinyon pine.—We found a close correlation (.998) between dry tree weight and maximum crown diameter. The small standard error of estimate of 0.038 suggests that tree weight can be estimated fairly accurately from maximum crown diameter (*table 2*). For example, the mean dry weight of groups of trees having maximum crown diameters identical to the study average D_{CM} can be estimated to within + or - 2 percent of their true weight 95 percent of the time, or actually + 2 percent and - 1.9 percent because of the double-logarithmic form of the estimating equation.

It is more difficult to estimate accurately the weight of individual trees from the equations. For example, the dry weight of a pinyon pine with D_{CM} identical to the study average can be estimated to within + or - 17.6 percent of its true weight with only a 1 chance in 20 of being wrong (*table 2*).

Accuracy of estimating the weight of individual trees and stands decreases progressively as D_{CM}'s depart from the mean in either direction.

Stem diameter at 1 foot, D_{S1}, was the next most accurate estimator of dry tree weight of pinyon pine (*table 2*). This variable was not tested for juniper. The remaining variables, in order of accuracy for estimating dry tree weight of pinyon pine were: average crown diameter, D_{CA}, and tree height, H_T.

Dry weight of the tree components—crown and root—also was correlated with maximum crown diameter of pinyon pine (*tables 3,4*). The independent variables, D_{CM}, and stem diameter at 1 foot, D_{S1}, showed to about equal advantage for estimating dry crown weight (tree less root) of pinyon pine (*table 3*). The remaining variables, in order of accuracy for estimating dry crown weight were: average crown diameter, D_{CA}, and the tree height, H_T.

Root weight showed more variation with maximum crown diameter than did crown weight—probably because of differences among trees in the amount of root extracted in up-rooting (*table 4*). The remaining variables in order of accuracy for estimating dry root weight were: average crown diameter, D_{CA}, stem diameter 1 foot, D_{S1}, and the tree height, H_T. For all sizes of trees, about 15 percent of the weight is in the roots. The corresponding figure for juniper roots is 16 percent of tree weight.

Utah juniper.—Dry tree weight and maximum crown diameter for juniper were highly correlated as indicated by the large R of .976 (*table 5*). The computed standard error of estimate was small. For example, the mean dry tree weight of populations of junipers having maximum crown diameters identical to the study average D_{CM} can be estimated to within + or - 7.7 percent of their true weight, with the customary small probability of being wrong. The tree weight of an individual juniper with D_{CM} identical to the study average can be estimated to + or - 61.2 percent of its true weight, with the customary small probability of being wrong (*table 5*). The corresponding values for pinyon pine were 2 percent and 17.6 percent.

The remaining variables, in order of accuracy for estimating dry tree weight of pinyon pine were: average crown diameter, D_{CA}, and tree height, H_T.

Dry weight of the tree components—root and crown (tree-less root)—also was closely correlated with maximum crown diameter of juniper (*tables 6,7*). The roots of two of the junipers were not analyzed. The same curve form as for the entire tree applied. The remaining variables, in descending order of accuracy for estimating dry crown weight and dry root weight of juniper were: average crown diameter, D_{CA}, and tree height, H_T.

Root weight of juniper appeared to correlate more closely with crown diameter than root weight of pinyon correlated with crown diameter or stem diameter. The reason may be that varying amounts of pinyon roots remained in the ground while most of the juniper root system was consistently uprooted.

About 16 percent of the total dry weight of a juniper tree was in the roots, regardless of size.

Distribution of Fuel Weight

Pinyon pine.—For the 6-inch diameter pinyon pine analyzed, material 1/2 inch or less in diameter accounted for half its total weight (*table 8; fig. 1*). The roots comprised 13.7 percent of the total weight, compared to an average of 15 percent for the 21 pinyons analyzed. A considerably larger proportion of the root weight was in the larger diameter classes than was the crown or above-ground portion of the tree.

tah juniper.—We found large differences between the small juniper tree (J-15) and the large one (J-16) that were analyzed intensively for distribution of fuel weight (*table 9; fig. 2*). The crown of the small tree has a much greater proportion of the total fuel weight in needles than the crown of the large tree: 45.9 percent versus 26.8 percent. Comparative percentages for other size classes to and including the 2- to 4-inch class were not greatly different for the two trees.

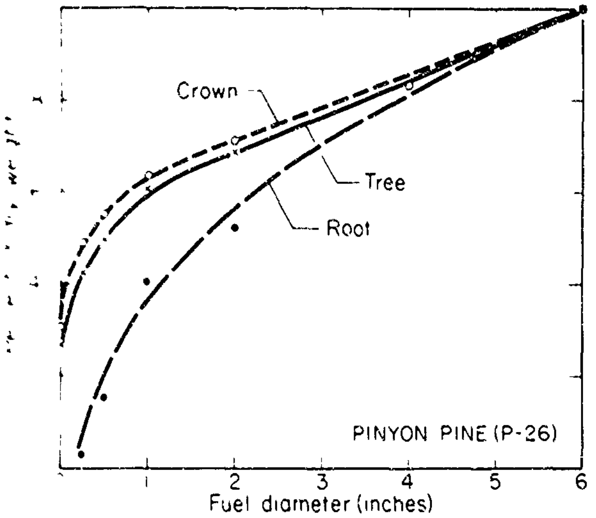

Figure 1.—*Distribution of dry weight by fuel diameter and tree component. Pinyon pine P-26, stem diameter 6 inches at 1-foot. Needles are plotted at zero diameter.*

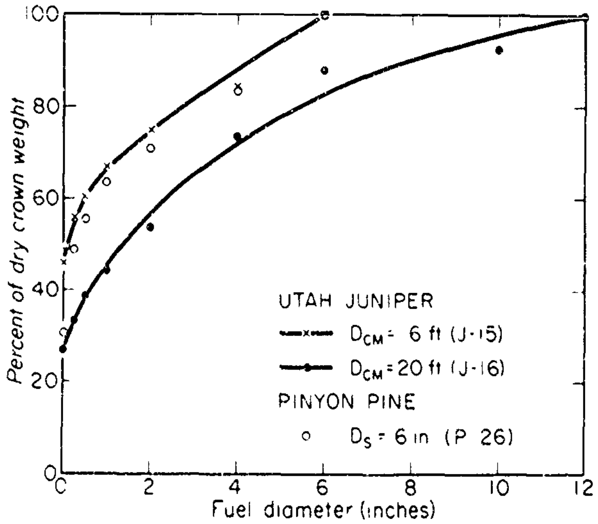

Figure 2.—*Distribution of dry weight by fuel diameter classes in crowns of Utah juniper and pinyon pine trees. Needles are plotted at zero diameter.*

Similarity Among Branches

In both pinyon pine and juniper the fuel size distributions of the sample 4-inch diameter branches from large trees were remarkably similar, although each branch was chosen at random from among many such branches in the crown of each tree (*tables 10, 11; figs. 3,4*). These results support the feasibility of using a sample stem-sample branch technique for analyzing large junipers.

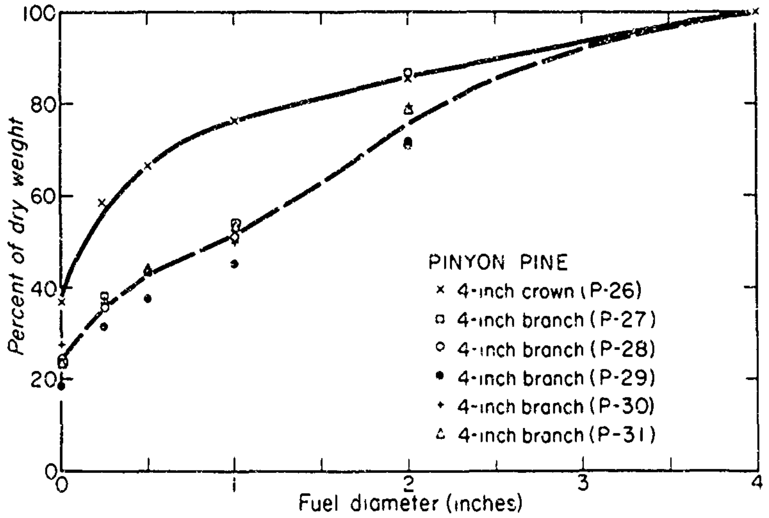

Figure 3.--*Distribution of dry weight by fuel diameter and tree components--branches and crown--of pinyon pine. Needles are plotted at zero diameter.*

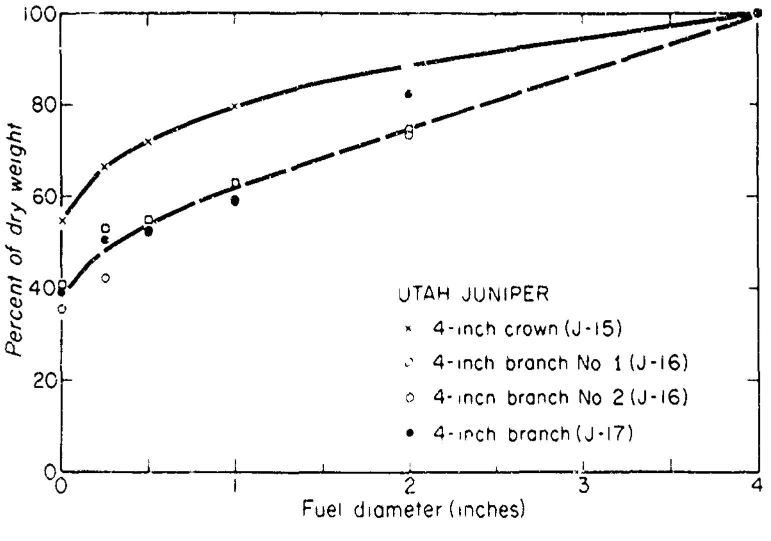

Figure 4.—*Distribution of dry weight by fuel diameter and tree components--branches and crown--of Utah juniper. Needles are plotted at zero diameter.*

Conclusions

On the basis of the findings, we concluded that:

1. Dry tree weight, dry crown weight, and dry root weight are closely correlated with maximum crown diameter, average crown diameter, and stem diameter at 1 foot for pinyon pine and with maximum crown diameter and average crown diameter for juniper, which has multiple stems.

Relationships are double logarithmic—fuel weight increases at an increasing rate with each unit increase in stem or crown diameter. Estimating equations for roots are less precise than those for the tree and the crown for both species, probably because of differences among trees in the amount of root extracted in uprooting. Root weight, on the average, bears a constant percent relationship to tree weight regardless of tree size: 15 percent for pinyon and 16 percent for juniper.

2. About 25 percent of the total dry weight of small pinyons may be in needles.

Another one-quarter of the tree weight is in twigs and rootlets 1/2 inch or less in diameter. A greater proportion of the root weight than crown weight is in the larger fuel-size classes.

3. The fuel size distribution of juniper roots was not determined, but ample data on the total root weight of juniper are available.

An estimate of the distribution of this weight, by size class, can be obtained by applying the data on distribution of pinyon roots. The roots of either species accounted for only a small percentage of the total weight of the tree. Large errors in the size distribution of roots would have only a small effect on the fuel size distribution of the tree.

4. The fuel size distribution curves for the small pinyon and small juniper crowns paralleled one another closely at fuel diameters larger than 1/4 inch.

This finding suggests that pinyon and juniper trees of similar size may have similar fuel size distributions.

5. Fuel size distribution among branches of identical girth from larger trees of either species appears to vary only slightly.

Three 4-inch diameter branches chosen at random from two junipers of similar size were similar in proportion of weight in needles and in five fuel diameter classes. Similar results were obtained with five branches from five pinyons. This finding supports the use of the sample branch technique for fuel size analyses.

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Appendix C

GAS ANALYSES IN LARGE FIRE EXPERIMENTS

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CONTENTS

Page

Introduction 34

Description of Experiments 35

Instrumentation 38

Discussion of Results 44

Fire Behavior 46

Life Hazard Implications and Environmental Exposure 51

Model Applications 55

Summary and Conclusions 60

Acknowledgments 61

References 90

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INTRODUCTION

Large experimental fires make measurements of fire characteristics possible and allow a range of prescribed initial conditions such as fuel moisture, loading, and geometry. They may be instrumented to yield measurements for evaluation of fire behavior and environmental effects.

Life hazard in mass fire environments has been a subject of study and speculation.[1] The chemical composition of the atmosphere in and around a mass fire area is recognized as one of the primary determinants of the degree of hazard. However, available field data for realistic assessment is scarce. Until the most recent Flambeau experimental fires, there have been few opportunities for study of fire areas greater than five to ten acres with fuel bed continuity and loading approximating those of an urban area. In recent experiments, a limited program of gas sampling and analysis was carried out in an effort to provide some of the desired data pertaining to life hazard in the open (fuel bare) regions between piles or burning units and in regions which shelter locations might be forced to rely for ventilation. The most recent experiment was instrumented expressly to provide further life hazard information in the zone of most probable human exposure.

Earlier experimental burns of smaller scale have provided information which may be used to compare the gross combustion behavior of various wildland fuels and fuel bed types with each other and with data from closed environment fires in real buildings. The latter comparisons may be of importance in judging the usefulness of the multiple pile wildland fuel plot as a physical model for urban areas and defining the differences which must be considered in applying the experimental data to particular questions.

Measurements of the composition of the gas in and above the active combustion zone bear on certain questions in the characterization of fire behavior and for development of mass fire models. Deviations from total oxidation stoichiometry for wood fuels may significantly affect calculated rates of energy release used in models. The vertical gas composition and dilution profile may be useful, particularly when coupled with velocity measurements or experimental fuel consumption rates. At least one convection column model requires mass flow rates and concentrations of fuel and product species as a function of height in the flame zone above a mass fire. Combustion product dilution may be studied and inflow composition to the fire estimated.

Large scale experiments provide input data for the problems related to real world mass fires, though they are difficult to design and instrument and costly to perform. They may, however, provide the only acceptable method close enough to reality to answer many of the posed questions and validate the models which have been or are yet to be developed.

DESCRIPTION OF EXPERIMENTS

Data are presented from thirteen U.S. Forest Service experimental fires. Six of these were from series 460 (Mono Lake) and 760 (Montgomery Pass), and ranged in array size from one to three hundred and forty-two piles of the type described as mixed fuel; 20 tons per pile, 46.7 feet square, seven feet high.[2] Fuel is principally local pinon and juniper. Results are presented for four fires from series 380 and two from series 428, described as heavy fuel plots and light fuel plots.[2] One experiment reported is a two-story house fire. The sampling systems and analytical instrumentation used in the experiments are described in the instrumentation section.

Fire 760-12 on September 29, 1967, was an eighteen by nineteen pile array with twenty-five foot streets. Gas sample inlets were placed in pairs of one six-inch and one five-foot height at each of three locations. The six inlets were numbered consecutively from high to low and from the deepest into the fire to the edge, (see Figure 1). The three pairs were all located in the aisle between pile rows 11 and 12; at the centerline of the J row, center of the intersection between the D and E rows, and at the centerline of the A row. These locations profiled the downwind half of the fire area. Gases from the six inlets were drawn through separate 5/8" OD aluminum tubes out of the fire to the instrument trailer approximately 400 feet away.

Fire 460-7 on June 14, 1966, was a fifteen by sixteen rectangular array with twenty-five foot streets. Gas sampling was in two locations, as shown in Figure 9 in order to determine concentrations in the streets. A continuous sample was drawn from the thirty foot level in location 1. Water vapor content was analyzed approximately thirty-four feet downstream and carbon monoxide, carbon dioxide, and oxygen approximately twelve hundred feet from the sampling point. Integrating sampler sets located at 1 and 4 shown on Figure 9 drew samples from one foot above ground level. Meteorological conditions prior to this burn were mild as might be expected for early summer; producing relatively low fuel moisture of 6% - 7% average moisture. The fire appeared to have a high burning rate and early peak intensity (approximately 5 minutes after ignition).

Fire 460-14 on December 6, 1965, was an eighteen pile square array with twenty-five foot streets. Grab samplers were located in locations 1, 2, 3, and 4, shown in Figure 11, and sampled at one foot above ground level. A continuous sample was drawn from the fifty foot level at location 1 in the center of the plot. The gas stream was analyzed approximately twelve hundred feet downstream from the inlet. This plot was covered with two to four inches of snow, producing high moisture burden. It appeared to have a low burning rate and no well defined intensity peak.

Fire 460-(Single Pile) on September 1, 1965, had a continuous sample initially drawing from the thirty foot level over the center of the pile, (location 1, Figure 12). Grab samplers were located at the base of this tower, sampling at one foot above ground level, and at ten, fifteen and twenty feet on a tower at location 2 to indicate external conditions. The continuous sample was analyzed approximately four hundred feet downstream of the sampling point. During the experiment the sampling tube separated, changing the sampling point to ground level. Both points, however, were in active flame zones. This fire appeared extremely intense with a well defined peak at four to five minutes after ignition. Since burning occurred in late summer, the moisture burden was low.

Fire 760-2 on May 15, 1964, was a six by six pile square array with twenty-five foot streets. A continuous sample was drawn from the twenty foot level above a pile (location 2, Figure 13), and analyzed six hundred feet downstream of the inlet. The supporting tower was damaged which changed the sampling point to ground level at a time between four and ten minutes after ignition. A grab sampler was located at the center of the first street intersection in from a corner sampling at one foot (location 1). This fire appeared to have a high burning rate and gave peak intensity at about 4 to 6 minutes after ignition.

Fire 760-1 on January 31, 1964, was a three by three pile square array with 115 foot streets (Figure 14). A continuous sample was drawn from twenty feet over a pile at location 1. The continuous inlet was in and out of active flame for the period from five to fifteen minutes after ignition. The individual piles burned with moderate rate in spite of the winter conditions.

Fire 380-5 on August 26, 1963, was a heavy fuel plot of approximately 105 foot diameter. A continuous sample was drawn from a point four feet above ground at the edge of the pile (Figure 15).

Fire 380-3 on August 15, 1963, was a heavy fuel plot of approximately 100 foot diameter. A continuous sample was drawn from a point four feet above ground inside the pile. The fire appeared to build up at a slow rate, but was intense over a prolonged time period (Figure 16).

Fire 380-2 on August 12, 1963, was a heavy fuel plot of approximately 118 foot diameter. A continuous sample was drawn from a point twenty feet above ground at the center of the pile (Figure 17).

Fire 380-1 on July 31, 1963, was a heavy fuel plot of approximately 120 foot diameter. A continuous sample was drawn from a point twenty feet above ground inside the pile (Figure 18).

Fire 428-1 on June 7, 1963, was a light fuel plot approximately 200 feet by 400 feet on a hillside with a 20% - 25% estimated slope. A continuous sample was drawn from approximately five feet above the ground at the location shown in Figure 19. Fire spread from the ignition points resulted in an uneven distribution of flaming over the plot area. The overall rate of burning and intensity appeared to be low.

Fire 428-3 on June 4, 1963, was light fuel plot approximately 100 feet by 300 feet. A continuous sample was drawn from a height of four feet at a point 50 feet into the pile on the southeast (300 feet) side (see Figure 20).

Fire 642-1H on February 28, 1964, was a two story dwelling in Riverside, California. A continuous gas sample was drawn from five feet above floor level within a first floor room. At a time between 24 and 28 minutes after ignition, shortly after flashover and appearance of external flames, the sample tube burned off where it entered the house. The house burned intensely as it became an open environment fire.

INSTRUMENTATION

The sampling system used on 760-12 was a bank of continuous analyzers sequencing six inlets. Gases from the six inlets were drawn through separate 5/8" OD aluminum tubes out of the fire to the instrument trailer approximately 400 feet away. Pressure in the six lines at the points of sample removal were kept constant. A timer sequenced six solenoid valves in branch lines allowing one sample at a time to be drawn through the bank of instruments by auxiliary pumps. The instrument bank ran at constant pressure and flow, exclusive of minor switching transients, and included MSA LIRA 300 nondispersive infrared analyzers for carbon monoxide and carbon dioxide and a Beckman F-3 fast flow fast response analyzer for oxygen content. The response time of the latter instrument governed the minimum cycle time between samples which was 18 seconds. This gave a total interval between sampling a given inlet of one minute forty-eight seconds. The discrete points in the reduced data are one minute and forty-eight seconds apart. The system is shown in Figure A. Data was recorded on three strip chart recorders with a time mark placed each time a solenoid was switched. Lag times from the inlet to the value at full

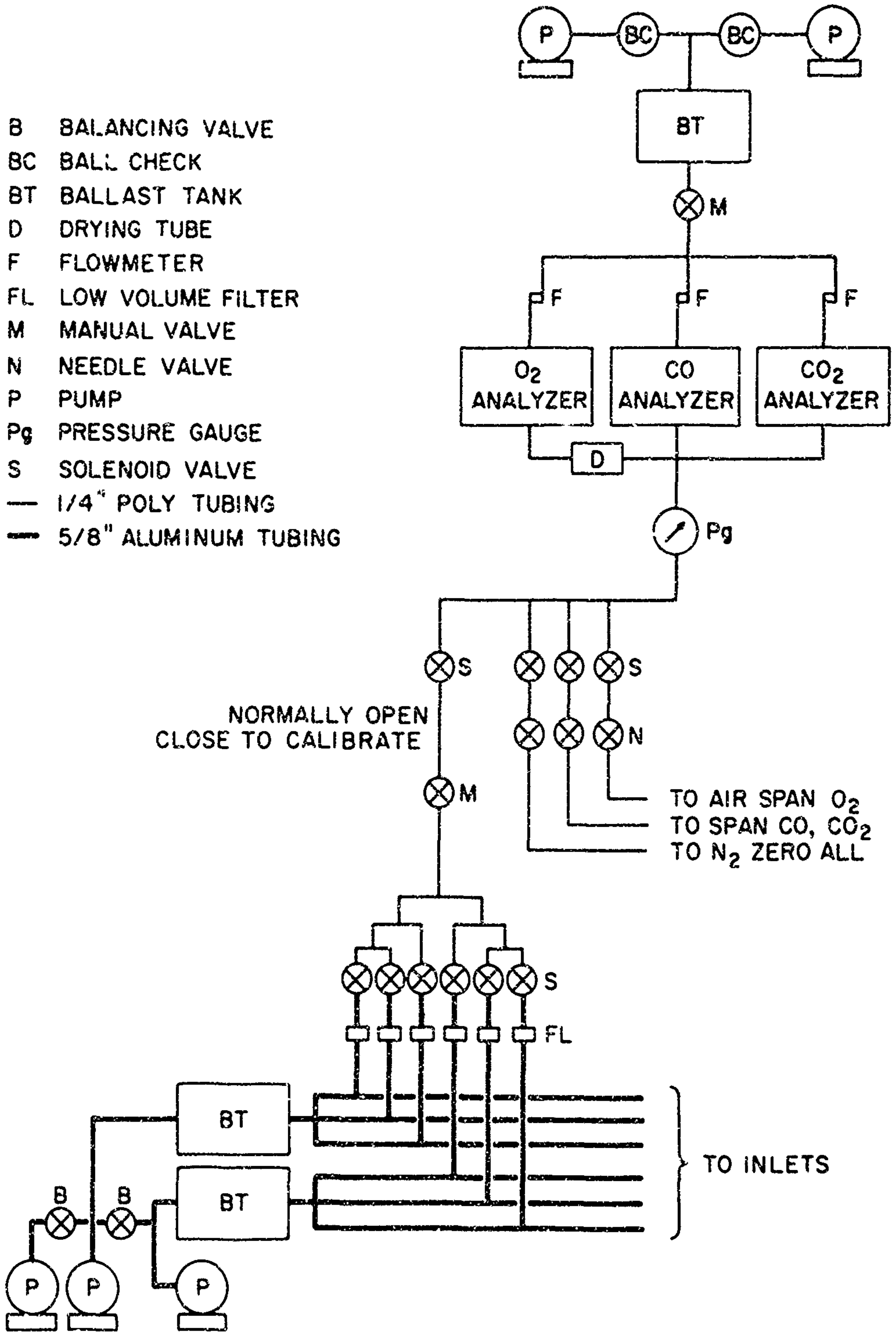

B BALANCING VALVE
BC BALL CHECK
BT BALLAST TANK
D DRYING TUBE
F FLOWMETER
FL LOW VOLUME FILTER
M MANUAL VALVE
N NEEDLE VALVE
P PUMP
Pg PRESSURE GAUGE
S SOLENOID VALVE
— 1/4" POLY TUBING
— 5/8" ALUMINUM TUBING
P
BC
BC
P
BT
M
F
F
F
O_2 ANALYZER
CO ANALYZER
CO_2 ANALYZER
D
Pg
S
S
NORMALLY OPEN
CLOSE TO CALIBRATE
N
M
TO AIR SPAN O_2
TO SPAN CO, CO_2
TO N_2 ZERO ALL
S
FL
BT
BT
TO INLETS
B
B
P
P
P

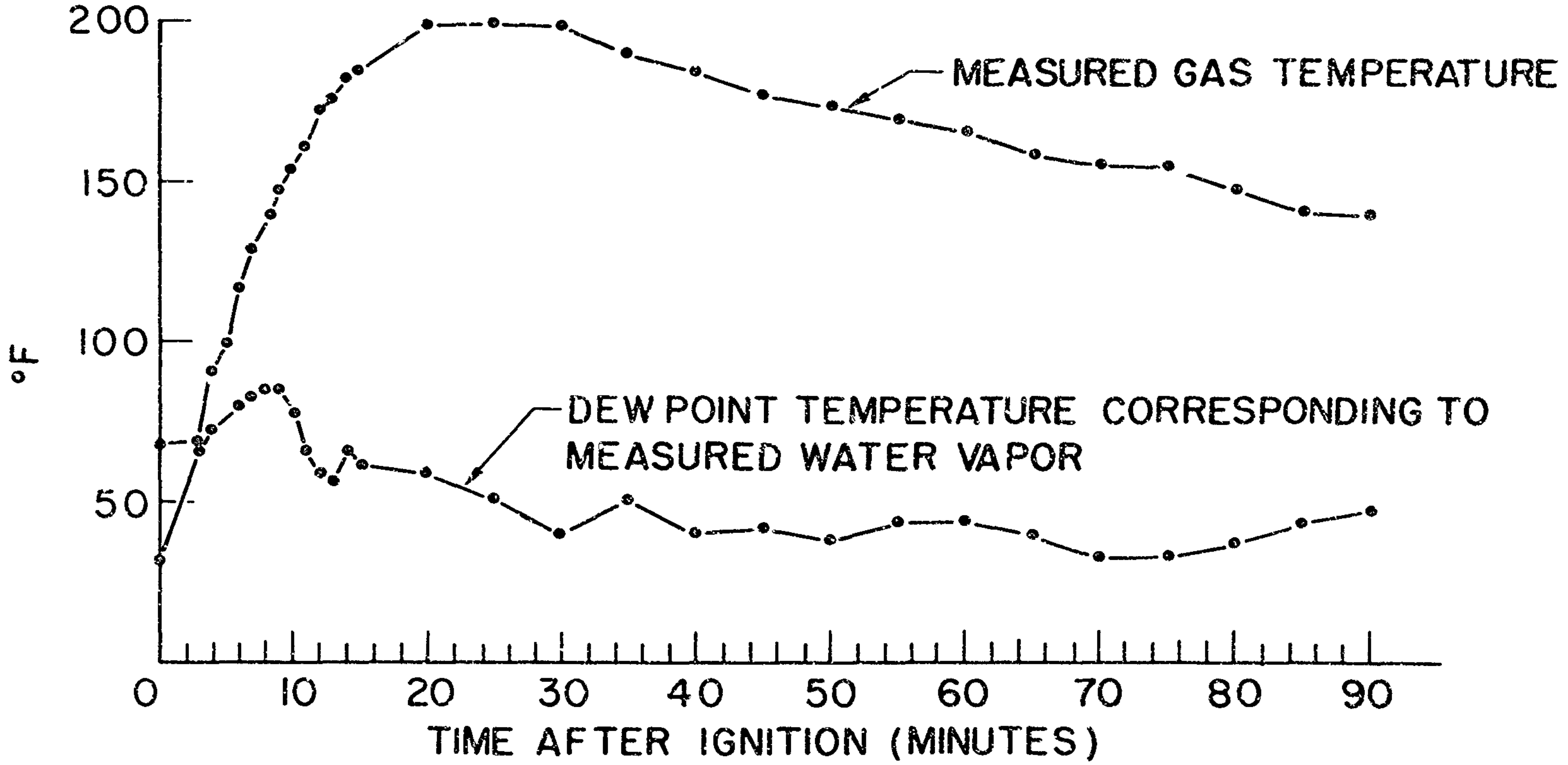
Figure A

response were determined and taken into account in the data reduction. Auxiliary measurements included temperature inside each of the inlets. A remote camera looking at inlets 5 and 6 was attached to the timer in such a way as to make one exposure each time a sample to be analyzed entered either inlet.

The gas sampling equipment used on all experiments except 760-12 involved three separate types. The continuous sampling system had a main pump to draw samples through 3/4" OD aluminum tubing and operated at a 3" - 10" Hg. line pressure drop to produce an average sample velocity of 20 ft/sec. Two instrumental analysis systems drew their samples from the main line. At a location close to the sample point, an MSA LIRA Model 300 nondispersive infrared analyzer with portable pumping system monitored water vapor continuously at constant instrument pressure. This location was used to avoid condensation in the tubing. Dew point versus sample temperature is plotted for one fire in Figure B. At a convenient location outside the fire a pump drew gas from the main sample line through three analyzers; two MSA LIRA 300's to monitor carbon monoxide and carbon dioxide, and a Beckman F-3 paramagnetic oxygen analyzer to monitor oxygen on a dry basis. All analyzer signals were recorded on Leeds and Northrup Model H potentiometric recorders. Response times were five seconds for the LIRA analyzers and forty seconds for the Beckman analyzer. All instruments are directly pressure sensitive and have known cross sensitivities. A manifold and valving system allowed for calibration of the instruments at operating pressures in the field. Uncertainties are noted on all figures for the continuous measurements and are of the form:

Uncertainties = ± (reading and calibration uncertainty + system pressure uncertainty)

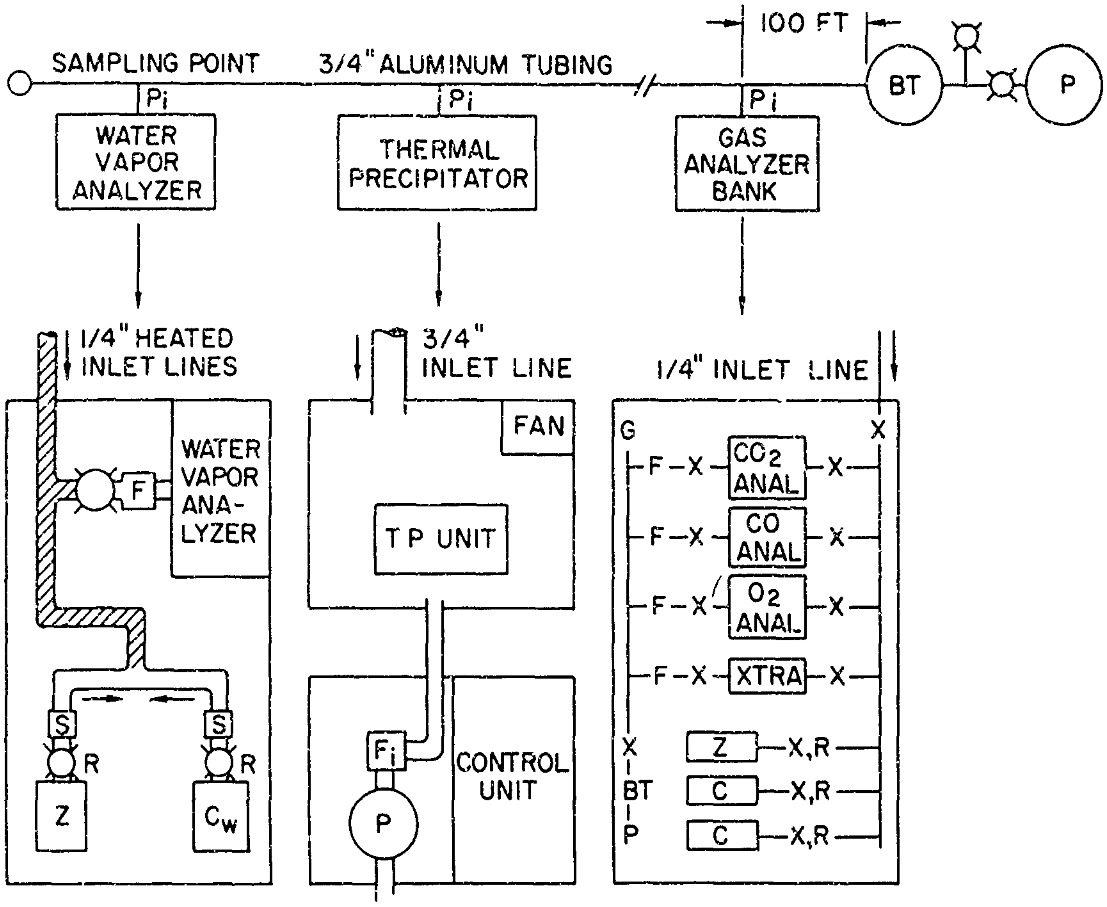
On selected fires particulate material was sampled from the gas stream near the water vapor analyzer using a thermal precipitator and examined with an electron microscope. The continuous analysis system is shown schematically in Figure C.



GAS TEMPERATURE AT WATER VAPOR ANALYZER

NOTES: 1. RELATIVE UNCERTAINTY FOR REPORTED TEMPERATURE ±5%
2. TEMPERATURES MEASURED 34 FEET DOWNSTREAM OF SAMPLE POINT

Figure B


100 FT
SAMPLING POINT
3/4" ALUMINUM TUBING
BT
P
Pi
Pi
Pi
WATER VAPOR ANALYZER
THERMAL PRECIPITATOR
GAS ANALYZER BANK
1/4" HEATED INLET LINES
3/4" INLET LINE
1/4" INLET LINE
WATER VAPOR ANA-LYZER
F
S
S
R
R
Z
C_W
FAN
T P UNIT
F_i
P
CONTROL UNIT
G
X
F
X
CO_2 ANAL
X
F
X
CO ANAL
X
F
X
O_2 ANAL
X
F
X
XTRA
X
X
BT
P
Z
X,R
C
X,R
C
X,R

F	FLOW METER
F_i	FILTER
G	GAUGE, PRESSURE/VACUUM
C_W	CALIBRATION GAS FOR H_2O ($n-C_4H_6$ IN N_2)
P	PUMP
X	VALVE
BT	BALLAST TANK
P_i	SIGNIFICANT PRESSURES
W	WATER VAPOR ANALYZER
TP	THERMAL PRECIPITATOR
Z	ZERO GAS SUPPLY
C	CALIBRATION GAS SUPPLY
R	PRESSURE REGULATOR
S	SOLENOID VALVE

CONTINUOUS ANALYSIS SYSTEM

Figure C

Sequential grab samplers consist of sets of five 300 cc double stopcock Pyrex gas bottles which are evacuated to 1 mm Hg. or less before the fire and opened remotely at selected times by electric solenoid valves. Approximately ten seconds is needed for the bottles to come to pressure equilibrium with the environment. Gas samples are analyzed for chemical composition by gas chromatography and nondispersive infrared analysis, Orsat technique, and wet chemical standard methods. The chromatograph used is a programmed temperature Loenco Model 70 Hi-Flex with molecular sieve columns for separation of fixed gases and lower hydrocarbons. Relative uncertainty with chromatography is less than ± 8%. For samples from fires 460-7 and 460-14, MSA LIRA model 200 nondispersive infrared analyzers were required for the low carbon monoxide and carbon dioxide concentrations, and gave larger relative uncertainties.

Integrating samplers consist of a set of six midget impingers, a self-contained pumping system, and a gas collection reservoir. The pump draws sample gases through each of the impingers at a known flow rate between 0.5 and 1.0 liters/min. The total flow is split on the exhaust side of the pump and a fraction collected in a 1.5 cu. foot aluminized Mylar bag housed in a protective aluminum tube. The total sampling time is variable and determined by the splitting ratio used. Gas components are selectively absorbed from the sample into the impinger solutions and their concentrations later determined. Below are examples of the components measured and analytical methods employed.

Components	Method	Uncertainty
Nitrogen dioxide	Modified Saltzman[3]	± 25%
Nitric Oxide	Permanganate Oxidation to NO_2-Modified Saltzman	± 25%
Aldehydes (+ Acetone)	Goldman-Yagoda[4] Bisulfite/Titrimetric	± 25%

The contents of the Mylar bag also represent an average composition over the sampling period. The composition is determined by the same methods used in analyses of grab samples, described above.

DISCUSSION OF RESULTS

The gas composition measurements appear to be internally consistent for mixed fuel plots, considering the interplot variability in fuel particle and bed characteristics, meteorological conditions, ignition pattern, and other parameters affecting fire behavior.

Discretion, however, is required in discussing and interpreting the data. The locations of the sampling points relative to the fuel and flaming combustion zone require careful attention in comparing between data from the various fires. The time dependence of the energy release rate and the associated flame zone height should also be noted; the relationship of the sampling point to the combustion zone does not remain fixed in time for any given fire. Compositions reported for sampling points in flame regions should not be interpreted as real combustion process compositions, as reactions may continue toward completion in the sample stream.

Quantitative comparisons between experimental fires, correlations of measured parameters, and comparison of peak values and durations should be tempered by a qualitative understanding of the fire. A plot with heavy moisture burden cannot be directly compared with one of otherwise identical characteristics. Further, the variables chosen for comparison should be carefully selected. For example, computed gas enthalpy and measured gas temperature, in streets, may compare differently with energy release rate.

On Fire 460-14-65 the thermal precipitator was buried at the base of the tower (location 1, Figure 11). Particle samples are collected on a moving slide which is examined by electron microscope. As the sampling point on this fire was not directly over the fire, it is not surprising that the counts are comparatively low. The micrographs were selected at intervals to cover the entire burn. There were no notable variations from the other time periods that were analyzed and therefore only a few representative micrographs have been presented.

#1878C - 10 minutes after ignition - Micrograph A
#1877C - 24 minutes after ignition - Micrograph B
#1883C - 50 minutes after ignition - Micrograph C

On Fire 760-2-64 the micrographs show a predominance of particles in the range between 1/100 and 2/10 of a micron with only an occasional particle as large as one micron. There is a difference in the appearance of the pictures between the heavy burning period and later stages.

#1829B - 3 minutes after ignition - Micrograph D
#1809B - 13 minutes after ignition - Micrograph E
#1831E - 21 minutes after ignition - Micrograph F
#1843E - 33 minutes after ignition - Micrograph G

Differences in the appearance of the micrographs for the house burn, 642-1H-64, may have been caused by the closed burning environment or the different fuel.

#1799 - 2 minutes after ignition - Micrograph H
#1801 - 15 minutes after ignition - Micrograph I
#1802 - 20 minutes after ignition - Micrograph J

The exploratory nature of the experiments to date permits consideration of the results in three areas. The discussion to follow will cover fire behavior, life hazard and model applications. It is an attempt on the part of the authors to demonstrate possible utilization and extension of the type of field data presented.

For convenience in discussing data, the following groupings are used:

I. Samples taken within the fuel beds and lower combustion zone (i. e., from regions where intense flaming combustion dominated over the burning period measured) -- Figures 12, 13, 15, 16, 17, and 19. Tables 3, 5 (location 1).

II. Samples taken directly over the fuel bed within the flaming combustion zone only intermittently --Figure 19 and 20.

III. Samples taken from outside the boundaries of fuel piles, in or over streets; not in the combustion zone -- Figures 2, 3, 4, 5, 6, 7, 8, 10, 11, and 18.

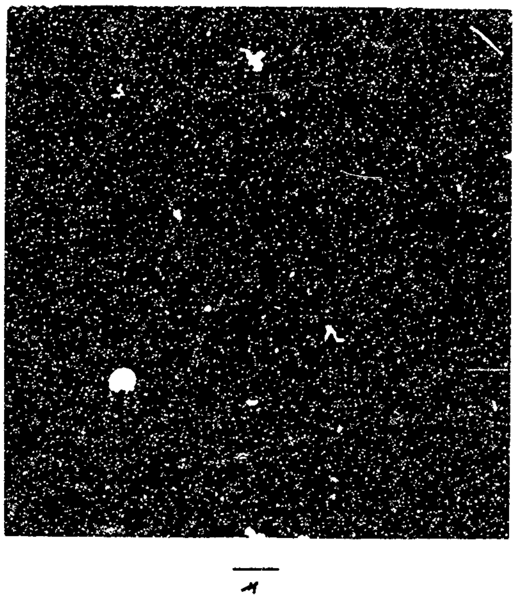
IV. Samples taken within a burning structure - Figure 21.

Fire Behavior

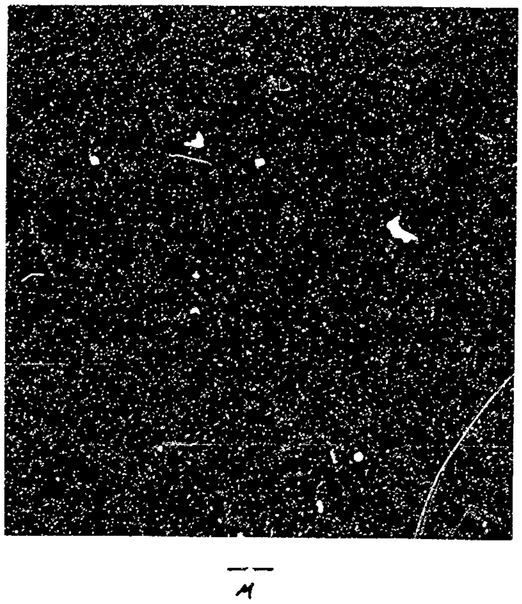
Measurements of gas composition provide the basis for some insights into fire behavior. Comparisons within Groups I and III provide some feeling for the relative effects of different fuel particle and fuel bed characteristics upon fire development, combustion rate, and combustion product distribution. Group III data may be analyzed for apparent effects of pile (or plume) interactions in experimental fires of different spacings and areas. Group I data may be compared with data from urban structure fires to reveal the differences in combustion gas characteristics between closed and open environments. Finally, possible behavior related parameters and ratios may be suggested for investigation.

Within Group I, Figures 17 and 19 show the distinct contrast between heavy fuel and light fuel fires which are described by Countryman.[2] Time between ignition and peak concentrations in Figure 19 is relatively long due primarily to fire spread through the fine fuel bed from igniters to gas inlet area. Figures 12, 17, and 19 show estimated durations above half peak (DHP) of 6, 12 and 2 minutes respectively for carbon dioxide, which follows the expected relationship with mean fuel diameter. The rise times from initial to peak combustion product concentrations are extremely fast for both fires having significant amounts of fine fuel (Figures 12 and 19). Within Group III, Figures 10 and 11 illustrate the relative effect of high moisture burden. The fluctuations in carbon dioxide concentration in Figure 11 are indicative of the long variable burning rate, and are in contrast with the defined peak in Figure 10. Absolute carbon dioxide concentration is also notably lower in Figure 11. Preliminary comparisons have been made between high and low concentrations of carbon dioxide and the magnitude of the vertical component of 'air' velocity near the sample point for fire 460-14-65 (Figure 11) and indicate a positive correlation between the two.

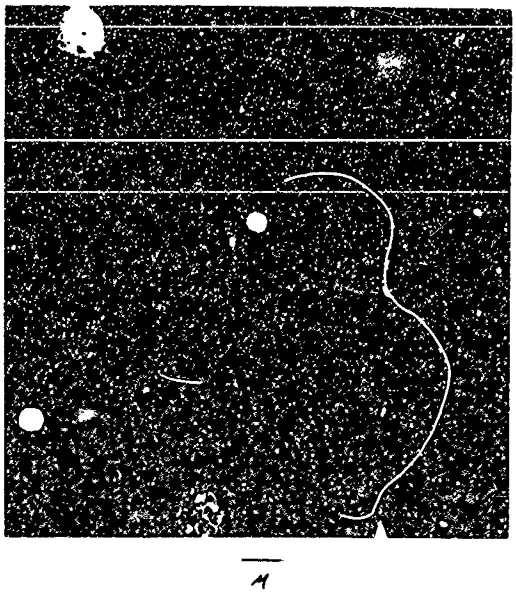
MICROGRAPHS
FIRE 460-14-65 FROM TOWER IN AISLE
PINION PINE



A

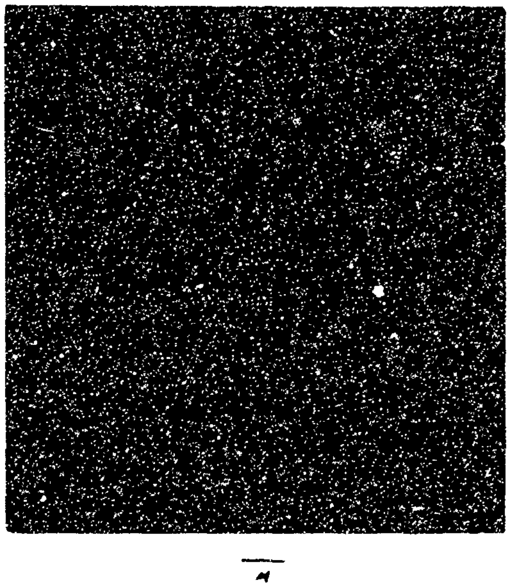


B

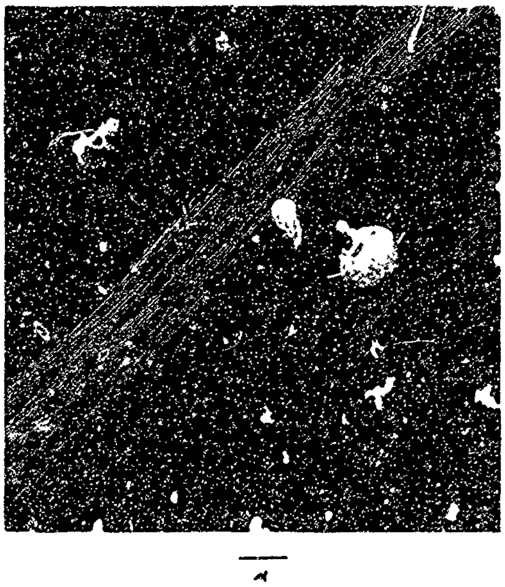


C

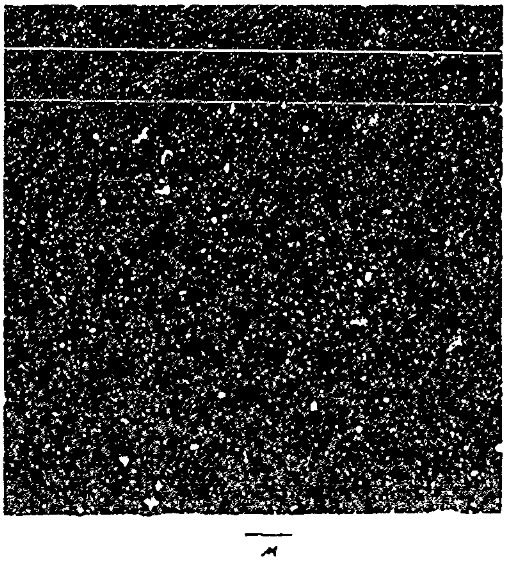
MICROGRAPHS
FIRE 760-2-64 FROM TOWER IN PILE
PINION PINE



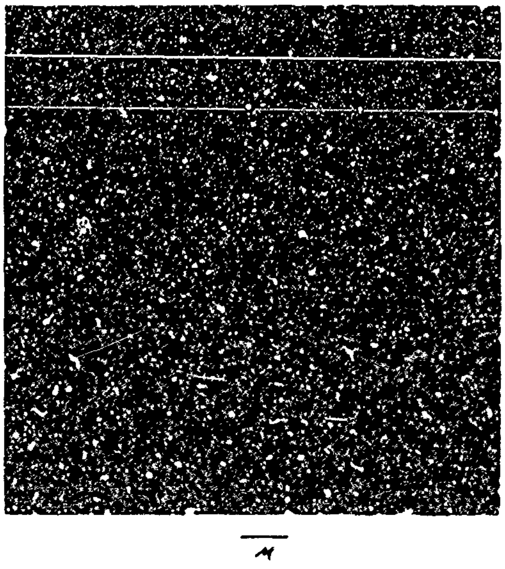
D



E



F

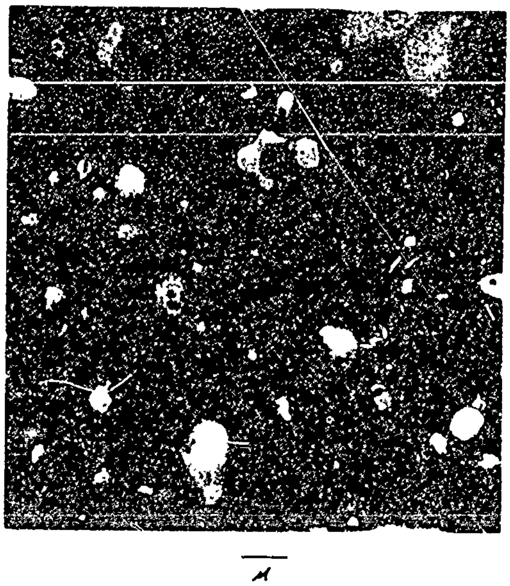


G

MICROGRAPHS
FIRE 642-1H-64 HOUSE BURN

H

I



J

Data from Group III appear to support the conclusion that high noxious gas concentrations do not exist in the streets of multiple pile fires. There is no definite pattern of increasing ground level gas concentration as the fire areas increase, however, a concentration difference has been measured along a street between the edge and center of a large fire plot, the concentration being greater at the center (Table 1). The opposite effect is seen in data from another fire (Figure 8) in which a more careful investigation of low level profiles was undertaken. The data from this fire indicate that between samples taken at the intersection of two piles the concentration of CO was greater at the edge. This may be explained by the fact that in each case the greater concentration was associated with the downwind sampling point.

The multiple pile experimental fires are intended to serve as physical simulations of fires involving urban areas.[2] The individual piles, however, have different characteristics than individual urban structures; notably, fuel size distribution, composition, and enclosure. Piles and structures may be expected to produce different spacial and temporal distributions of combustion products, which makes it difficult to directly translate experimental fire gas measurements to urban fire situations.

Differences between combustion product buildup in houses and product evolution in well ventilated fuel piles show in comparison of Figure 21 with data from Group I. For the latter, rise times to peak concentrations are faster, peaks generally lower and peak durations between one-fourth and one-half of those in closed environments. Figures 12 and 13 show significant differences though both samples were taken within intensely burning piles at or near ground levels; however, the inlet opening for the former was insulated from direct or close contact with the fuels, where the latter was covered with burning material in close contact.

In general the mixed fuel piles provide "internal" conditions in the periods after peak concentrations which may be comparable to house fires after they enter the "open environment" burning phase. Aggregates of such piles may be expected to provide interactions during and following the peak burning period not unlike those expected between totally involved groups of urban structures.

Dilution ratios based upon measured carbon dioxide concentrations may be useful in estimating air inflow to the fire and provide a better understanding of the relationship between the combustion zones and the surrounding environment. They may also be used as a basis for comparing locations in the environment and the associated environmental exposure to man. Minimum required air supplied to the combustion zone would result in a composition of combustion product gases with approximately a 20% concentration of carbon dioxide, based on complete oxidation on a dry gas analysis basis. In experimental fires, however, air is plentiful and the fuel is accessible. Measurements made in the combustion zones show that 10% carbon dioxide is about the maximum encountered in the experimental fire conditions; indicating a 100% average excess of air. For purposes of discussion, a value of 10% carbon dioxide is therefore used to represent combustion zone concentrations and serve as a basis for dilution calculations. The dilution at a sampling point is then defined as the ratio of the air to combustion product gases required to give the measured concentration, or $D_r = (10-X)/X$, where X is the measured carbon dioxide concentration and D_r is the dilution ratio required to produce it from a 10% carbon dioxide combustion product source.

Integrated samples collected at ground level in the streets of fire 460-7 (Table 1) give computed dilution ratios of 26:1 near the center of the plot and 90:1 near the edge. Fire 760-1 (Figure 14) results give dilutions of 10:1 to 30:1 which might be expected at the edge of the combustion zone, and a single peak of short duration giving a 1.2:1 dilution indicative of flame at the sample point which was 20 feet above ground level over the center of the pile. Samples taken from the fuel bed in fire 380-3, a heavy fuel plot, indicated dilutions from 0.2:1 to 2:1 as expected in the active combustion zone, near peak intensity.

Life Hazard Implications and Environmental Exposure

Combustion gases within mass fire environments may contain noxious substances which contribute significantly to the overall life hazard and constrain human activities during critical time periods. The gaseous fire environment may affect chances of personnel survival,[1,6] hamper postattack access to incendiary warfare zones for rescue, recovery, and military operations; and reduce the probability of human escape from the areas.

Both physiological and psychological factors may be expected to influence the net environmental hazard to exposed humans. Physiologically, carbon monoxide poisoning, oxygen deficiency, heat transfer to the body, accelerated respiration and blood circulation may combine (synergistically) to cause early collapse or death. The effects of smoke and hot gas inhalation, eye irritation and reduced visibility and heat discomfort may cause confusion and panic and may debilitate the performance of fire fighting, recovery, and rescue personnel.

Extensive treatment of the experimental fire data taken to date with respect to these considerations is beyond the scope of this paper. However, there are four aspects of interest to the authors which it is felt deserve brief mention, namely: applicability of experimental data to urban area hazard estimation; measured street concentration versus other experimental parameters; overall environmental exposure parameters; and minor gas components of potential significance. The first two of these were introduced in the previous section.

The potential hazard to personnel from buildup and transport of combustion product gases within burning structures may be obtained. The data in Figure 21 are in general agreement with this range of values and, as mentioned in the previous section, are in some contrast with experimental fire data in Group I.

The direct applicability of the experimental fire data to urban mass fire hazard estimation is dependent upon the validity of the multiple pile experimental fire as a physical simulation model. If the difference in combustion product buildup and release rate between experimental piles and urban area structures can be analytically defined, it may be possible to make direct use of some of the experimental fire results for prediction of environmental hazards in urban situations.

Interpreted within the context of the experiments, data from different multiple pile fires may allow one to infer relationships between hazard from (or concentrations of) combustion product gases and other 'mass' fire parameters. For example, one might test for a relationship between street concentrations of combustion products and the extent of area burning around the sampling location, or independently, the rate of energy release per unit area. As mentioned in the preceding section, the data from different experimental fires to date do not reveal any definite relationship between combustion gas concentrations at ground level in the streets and the extent of surrounding fire area, but a factor of three difference in carbon dioxide concentrations between the edge (in 65 feet) and center of a 30 acre plot has been indicated. Available data is very limited, and extrapolation to larger fire areas would be speculation. Qualitatively, the effect of high versus low energy release rate is indicated by the difference between data in Tables 1 and 3 and that of Table 2.

Ground level samples taken in the streets gave average combustion product concentrations (e.g., carbon monoxide) which were below hazardous levels[11] for the periods sampled (Table 6, Figures 2-7). This statement should not be construed to mean that survival would have been assured or even remotely possible for a human directly exposed to the environment. First, because many of the measurements were for time-averaged composition or grab samples and therefore tend to disguise or miss the peak levels, and second, because the gas composition is obviously only one factor in the overall exposure and even its effects are ill-defined for multicomponent systems. It can probably be safely said, however, that a shelter vented to the ground level street environment would have been presented little or no problem from the standpoint of gas toxicity, particularly if isolation from the vent gases could have been obtained for the 10-20 minutes during peak fire activity.

The matter of overall direct exposure, however, is worth coming back to, as it speaks to the question of escape from and access to fire areas. Personnel exposed to the fire environment can survive only if the body temperature stays within a few degrees of normal. Collapse and death may result in a few minutes if conductive, convective, radiative and evaporative heat dissipation mechanisms are affected so that a rapid body temperature rise occurs. From this standpoint, water vapor concentration is an important parameter in overall environmental exposure, as it affects the evaporative mechanism and largely determines the enthalpy of the atmosphere. Water vapor concentrations as high as 10% of the combustion gas volume have been measured during the early stages of the experimental fires, dropping to 1% in the latter stages. The moisture burden is apparently driven from the fuel quite disproportionally to fuel consumption. As a result, high exposures to very humid atmospheres are possible in the initial phases of a fire, which may significantly shorten the survival time estimated on the basis of temperature alone and affect shelter ventilation and heating.

The complexity of the overall environmental exposure within the fire area at various stages in the fire history suggests the desirability of developing empirical relations between easily measurable parameters and the associated effect of exposure on man. Experimental results indicate a relationship between carbon dioxide concentration, gross gas composition, and proximity to the combustion zone. A tabulation of the order of magnitude for an empirical relationship is suggested as follows:

Location of Experimental Measurement	Measured CO_2	Dilution Ratio-D_r	Effect of Associated Conditions of Man
Flaming Combustion Zone	10%	0:1	Rapidly Fatal (seconds)
Just Ourside or Above Flame Zone (20-60' above ground level)	1%	10:1	Fatal on Short Exposure (seconds - low minutes)
Adjacent to Piles, in Streets at Ground Level	0.1%	100:0	Tolerable for Short Exposure (minutes)
Outside of Fire Zone	0.01%	1000:1	Tolerable for Prolonged Exposures (hours +)

In addition to the major components of the atmosphere within experimental fire environments, some of the minor components have been measured, Aldehydes are known to be eye irritants and have been found in concentrations of 20-30 parts per million. Oxides of nitrogen, which are formed at high temperatures by direct oxidation of nitrogen in air, have been measured in flame regions at concentrations as high as 20 ppm in experimental fires and may represent a more significant hazard in the case of high nitrogen content fuels. Smoke has been collected in preliminary experiments using a thermal precipitator, some results being shown on pages 14, 15, and 16.

Model Applications

The gas composition measurements may have application to the development and testing of fire and convection column models. In some cases, gas composition values are required as direct input data for model calculations; in others, experimentally determined parameters required in model evaluation may be altered by considerations related to gas composition.

As an example of the former case, the model developed by Nielson, et al.,[5, 9] might be evaluated for specific fires if the concentrations of fuel gas (all combustibles), oxygen and nitrogen were known as a function of height. In addition, estimates of entrainment above the combustion zone might be obtained from the vertical profile of component concentrations (dilutions). Data gathered in past experiments, however, are difficult to apply to these requirements.

The second case is demonstrated by the use of measured water vapor and carbon dioxide to develop a modifier of energy release rate calculated from weight-loss platform data.

An extremely simplified statement of the stoichiometric reaction for total oxidation of dry natural wood fuels, is:

$$4\,C_6H_9O_4 + 25\,O_2 \longrightarrow 24\,CO_2 + 18\,H_2O \qquad (1)$$

If Y is taken as the water released per 4 $C_6H_9O_4$ formula weights in excess of the expected 18 formula weights, an equivalent simple equation for natural wood fuel with mositure content would be:

$$4\,C_6H_9O_4 + 25\,O_2 + Y\,H_2O \longrightarrow 24\,CO_2 + (18+Y)\,H_2O \qquad (2)$$

A dry fuel oxidizing stoichiometrically would be expected to give H_2O and CO_2 as products in the molar ratio 18/24 or 0.75 whereas a fuel with moisture content would be expected to give an H_2O/CO_2 ratio of $(18+Y)/24$. Such a ratio can be labeled R and be evaluated from experimentally measured water vapor and carbon dioxide concentrations.

Energy release rates calculated from experimental weight loss rate $(\Delta W/\Delta t)$ and energy of reaction for wood fuel, E_r, may require correction due to deviations from stoichiometry and nonlinear release of fuel moisture with fuel combustion. Weight loss can be expressed as the sum of dry fuel and moisture or

$$\Delta W = \Delta F + \Delta M \qquad (3)$$

Where: ΔW = weight loss

ΔF = portion of weight composed of dry fuel

ΔM = portion of weight composed of moisture

It is convenient to define the fraction of the weight loss composed of fuel (ΔF) as:

$$\Delta F = \left[4(145)/\left(4(145) + 18Y\right)\right] \Delta W = (f)\Delta W \qquad (4)$$

The remainder of the weight loss, ΔM, is the complement of ΔF:

$$\Delta M = \left[18Y/\left(4(145) + 18Y\right)\right] \Delta W = (m)\Delta W \qquad (5)$$

The measured weight loss can be corrected to true fuel weight loss and related to total energy release rate by the equation:

$$\Delta E = (f)\,\Delta W(E_r) \qquad (6)$$

An additional correction approximation can be made if it is desired to examine the actual energy available in the combustion zone, by subtracting the latent heat associated with the complementary water fraction. This correction is:

$$-(m)\Delta W(h_v) \qquad (7)$$

where h_v is the latent heat of vaporization of water. Thus the estimated energy release rate in the combustion zone is:

$$E \text{ (in combustion zone)} = (f)(E_r)\Delta W - (m)(h_v)\Delta W \qquad (8)$$

For purposes of calculation (f) and (m) may be redefined in terms of the measured ratio $\overline{R}$ (average R over time t) as follows:

$$(f) = 4(145)/4(145) + 18\,(24\,\overline{R} - 18) \qquad (9)$$

$$(m) = 18(24\,\overline{R} - 18)/4(145) + 18(24\,\overline{R} - 18) \qquad (10)$$

The table below gives computed correction factors for energy release rate based on H_2O and CO_2 measurements derived from Equations 9 and 10 for selected time intervals from two experimental fires.

ENERGY RELEASE RATE CORRECTION FACTORS

Experimental Fire	Time After Ign:Min	$\overline{R}$ for t	(f)	(m)
460-7	0-5	2.1	0.5	0.50
	5-10	4.8	0.25	0.75
	10-15	3.0	0.38	0.62
	15-20	2.2	0.48	0.52
	20-25	1.8	0.50	0.50
760-1	0-5	1.2	0.73	0.27
	5-10	2.9	0.38	0.62
	10-15	6.8	0.18	0.82
	15-20	10.0	0.13	0.87

The following assumptions and approximations are essential to the above discussion:

1. The contribution to R from ground moisture release is considered negligible.
2. Carbon monoxide effect on R (equivalent carbon dioxide) is ignored for simplification. Inclusion would decrease R by 5-10% but alter the reaction energy assumption.
3. Weight loss as carbon particulate and unburned organics is ignored, as quantitative data is not available.
4. The chemical reaction equation is not represented as physically accurate in natural burning processes, but may be considered true for bomb calorimetric determination of the energy of reaction.
5. $C_6H_9O_4$ is taken as the average empirical equation for wood fuels. It has been validated in laboratory analyses by the Pregl combustion method applied to sixteen samples of pinon and juniper. (Table 7)
6. Identical ratios are assumed for the sampling point used and a hypothetical location over the weight loss platform.
7. Water is assumed to remain in the vapor phase in the combustion zone.
8. The calculated R or $\bar{R}$ from field gas measurements use water vapor concentration corrected for contribution from relative humidity and carbon dioxide corrected to a "wet gas" basis.

The treatment above is based upon an extreme simplification of the combustion process. A better approach, applicable to the general case of nonstoichiometric oxidation, rather than simple disproportionate fuel moisture release, would require a variable stoichiometry reaction expression with inclusion of reaction products such as carbon monoxide and free carbon, both as particle load (weight loss) and char (weight remaining). Such a treatment would then apply a variable heat of reaction dependent upon the exact stoichiometry computed from experimental determination of gas concentrations and smoke density over the time interval selected. The illustration used in this paper is supplied as a first approximation, as data for a more sophisticated treatment are not currently available.

Other possible applications of gas composition data are in the estimation of convection column opacity to thermal radiation[10] and definition of conceptualized fire zones.[1]

SUMMARY AND CONCLUSIONS

Systems developed to sample and analyze gases from experimental fires have provided data which appears to be consistent with the general pattern of behavior of the fires and with other data collected. The capability of the system prior to Fire 760-12 was constrainted primarily by the limited amount of continuous analysis equipment available, but this has been partially remedied by the later sequenced system.

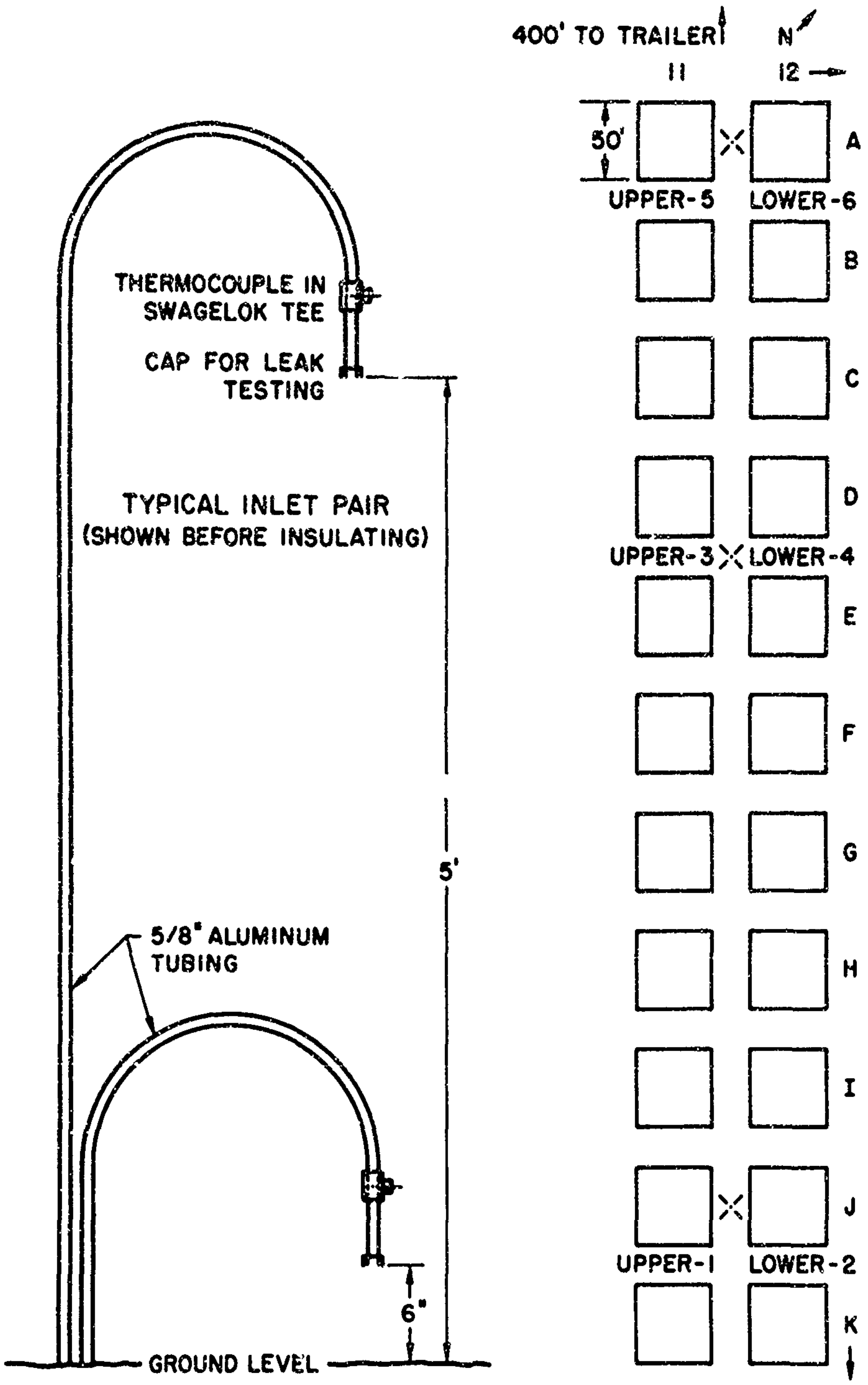
The following general conclusions are suggested by the results to date:

1. Gas analysis data is of importance in defining fire behavior, and comparing between experimental fires, in evaluating mass fire related hazards, and in testing and providing valid data for fire models.
2. The measurement of water vapor concentration is essential to an understanding of mass fire, from the standpoint of the defining internal environmental conditions, defining total human exposure, and as a means of relating the combustion process to fuel parameters and true energy release rate.
3. Dilution ratios based upon carbon dioxide concentrations or other gas component measurements can provide broad insight for study of interactions within the mass fire system and may be used as the basis for empirical relationships between measurable parameters and complex effects associated with them. In addition, dilution ratios may provide a basis, with other measurements, for the understanding of mass transport in the fire environment.
4. Smoke analyses are required in order to better understand the gross combustion process, and to evaluate hazard to human life. Photomicrographs of particulate material in the atmosphere of three fires are shown. These give indication of the nature of the suspended residue left in the air by combustion of forest and urban fuels.

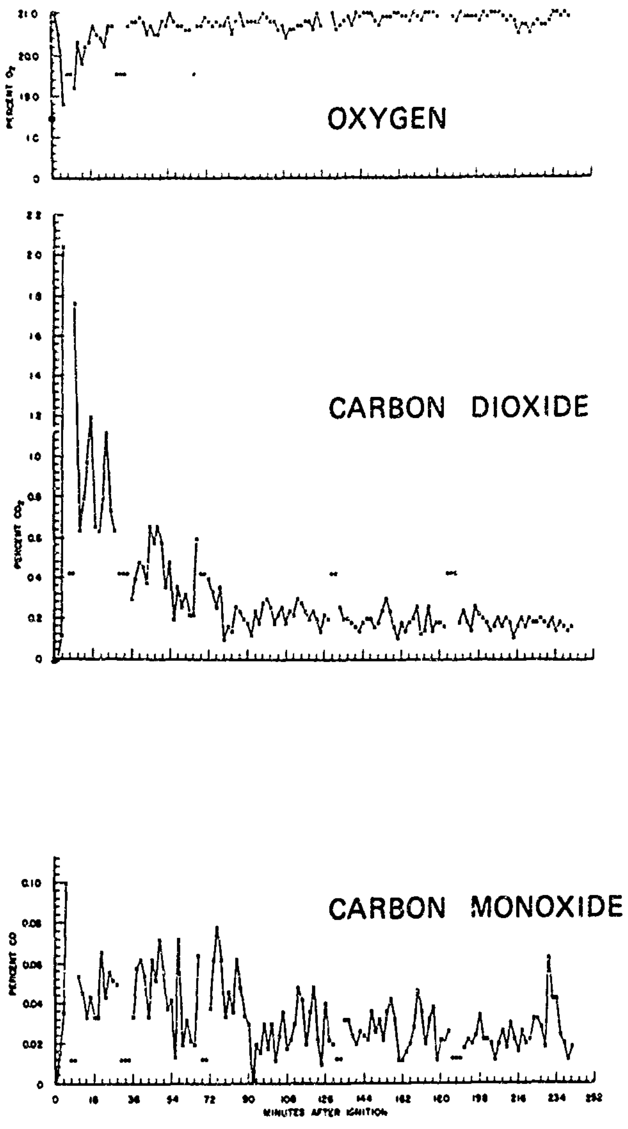
[illegible] Analyses of gases in the [illegible] of large experimental fires [illegible] data suggest that sufficient oxygen for survival is available at ground level in such locations and that noxious gas concentrations are generally below hazardous levels over most of the fire history. An insufficient data base exists at present for extrapolation of this conclusion to analogous urban areas or very large mass fires.

ACKNOWLEDGMENT:

This work has been sponsored by and carried out in close cooperation with the Forest Service, U.S. Department of Agriculture. We would like to thank Mr. Loyal Smith and Mr. John Murray of the Forest Service, Fire Research Laboratory, for their valuable assistance in the field, and Mr. R.W. Fekete and the UCLA Engineering students who spent their summers installing field equipment.

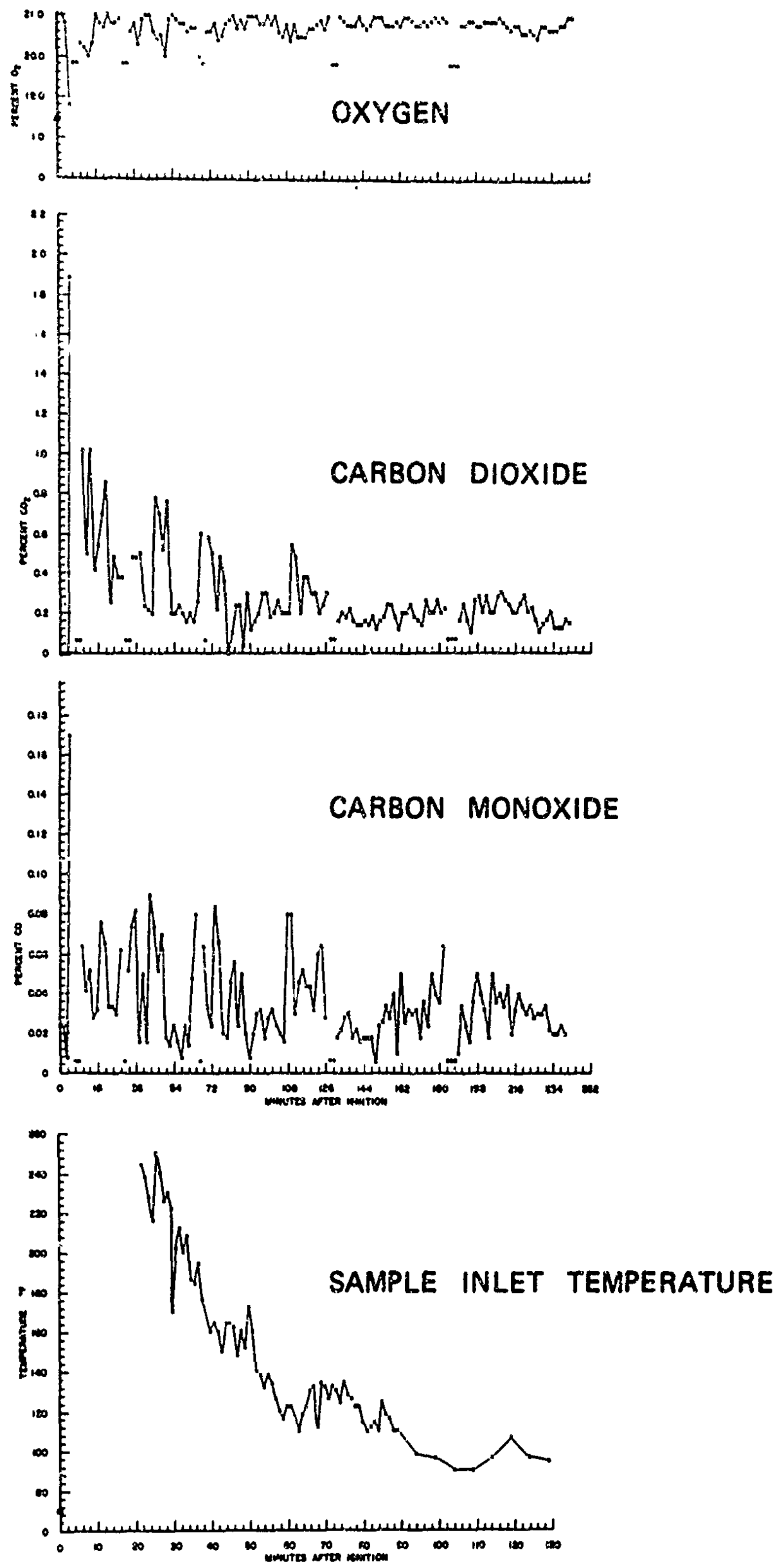

400' TO TRAILER
N
11
12
50'
A
UPPER-5
LOWER-6
B
C
D
UPPER-3
LOWER-4
E
F
G
H
I
J
UPPER-1
LOWER-2
K
THERMOCOUPLE IN SWAGELOK TEE
CAP FOR LEAK TESTING
TYPICAL INLET PAIR (SHOWN BEFORE INSULATING)
5'
5/8" ALUMINUM TUBING
6"
GROUND LEVEL

INLET AND THERMOCOUPLE LOCATION KEY
U.S. FOREST SERVICE FIRE 760-12-67
Figure 1

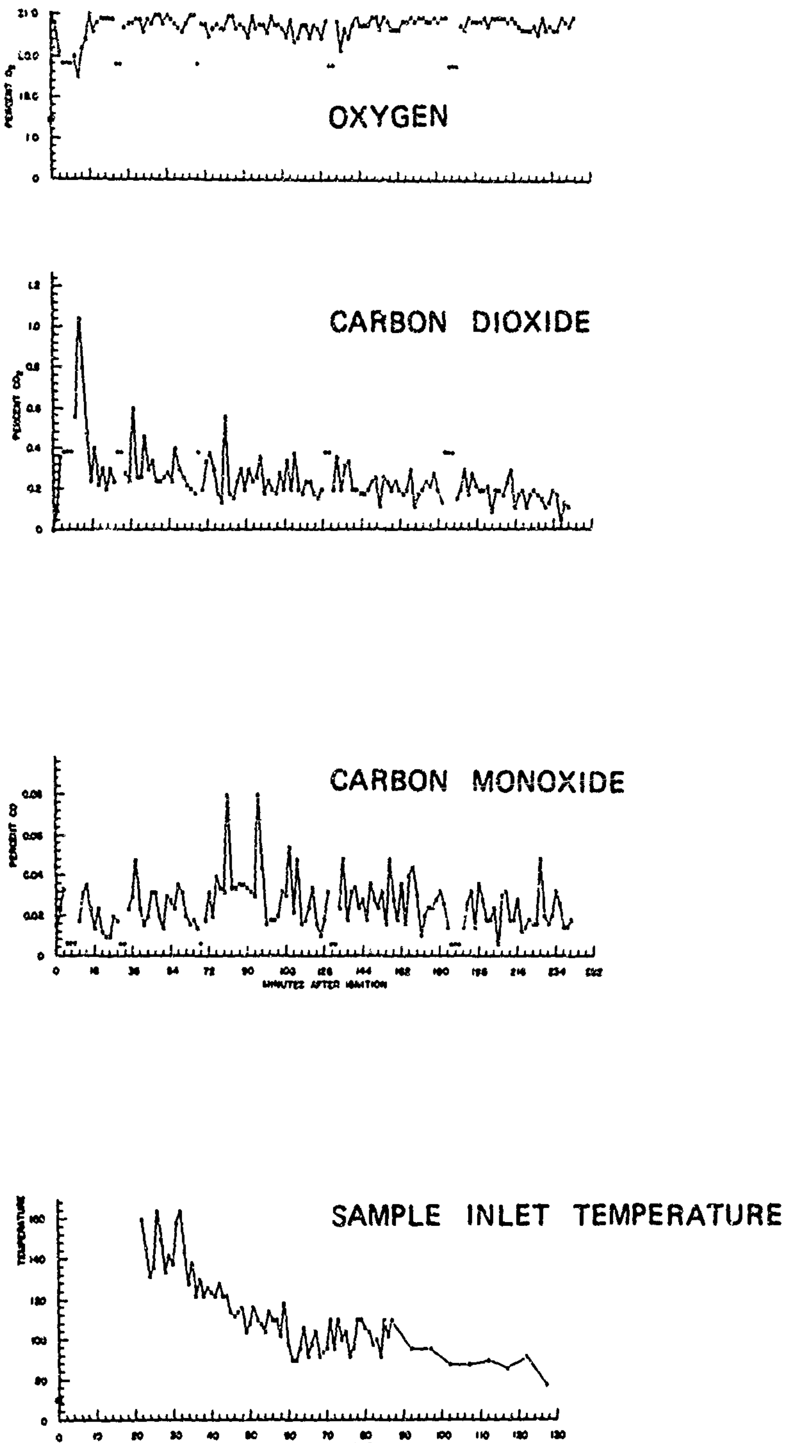


GAS ANALYSIS DATA – INLET NUMBER 1
U.S. FOREST SERVICE FIRE 760-12-67
SEPTEMBER 29, 1967
Figure 2

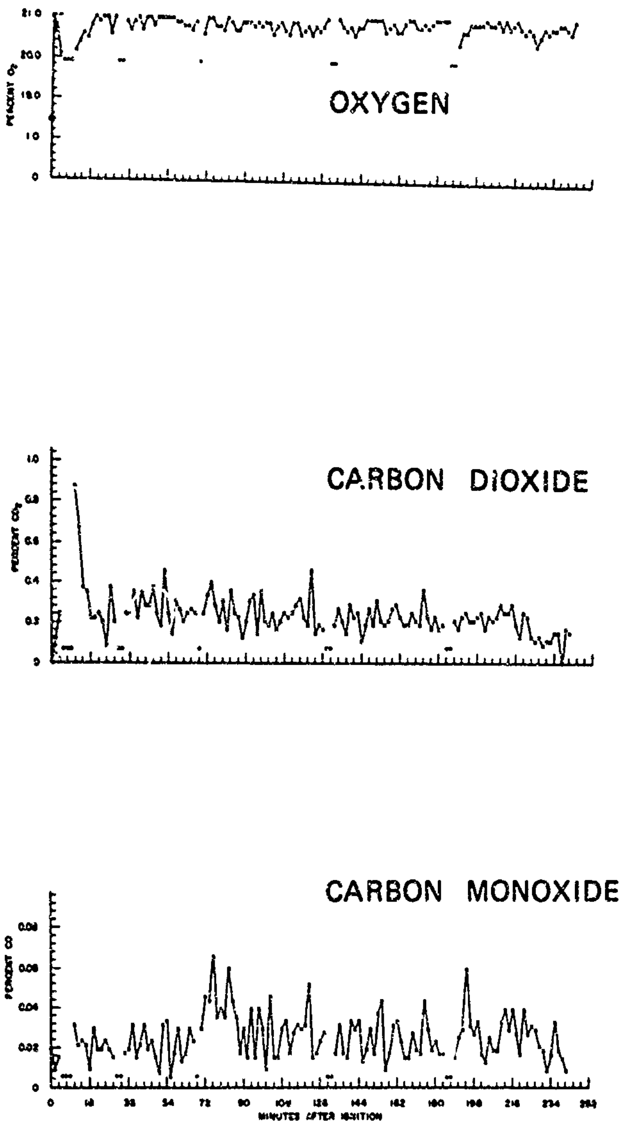
(Points not connected on Figures 2 through 7 represent calibration checks.)



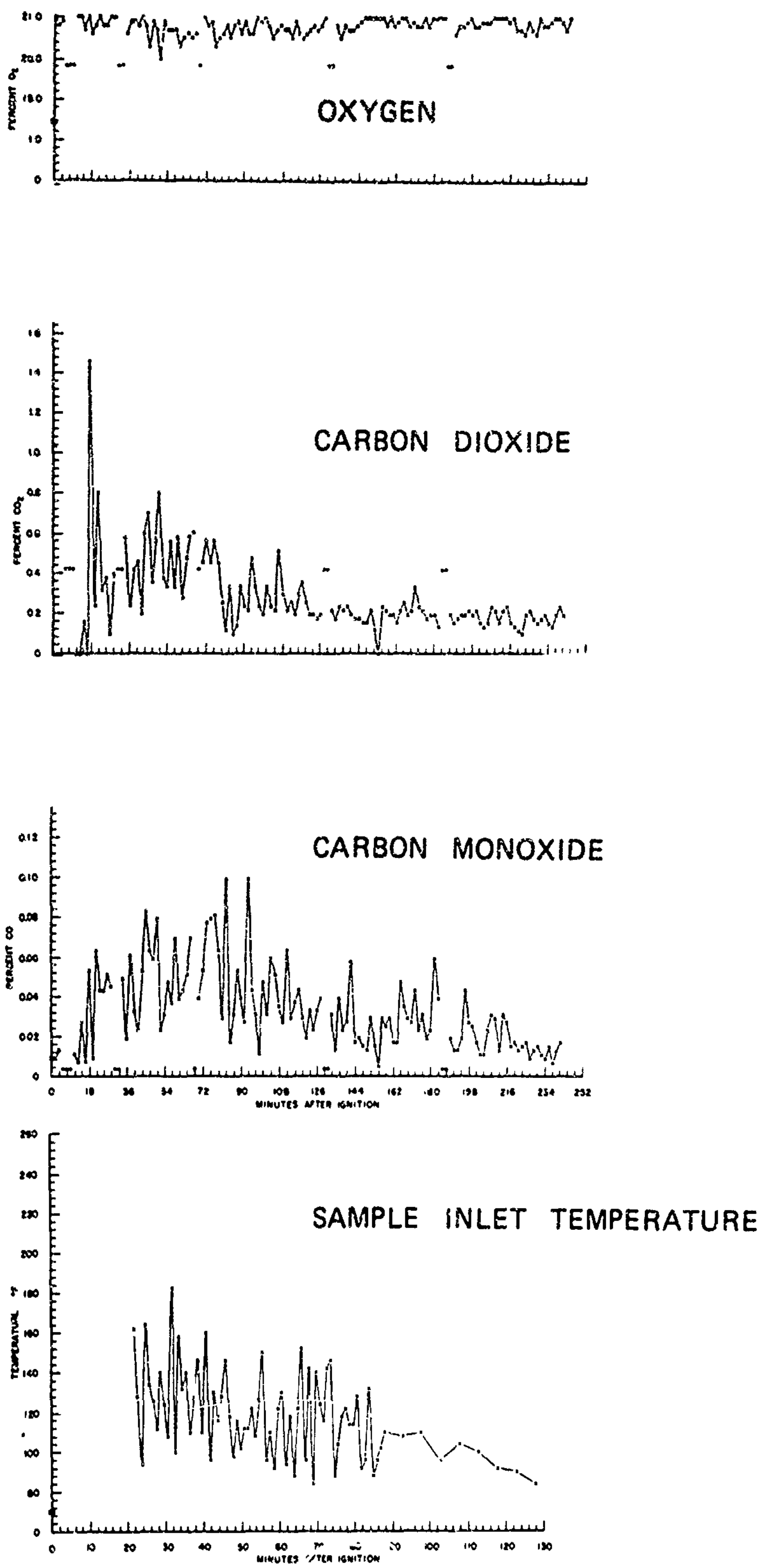
GAS ANALYSIS AND TEMPERATURE DATA – INLET NUMBER 2
U.S. FOREST SERVICE FIRE 760-12-67
SEPTEMBER 29, 1967
Figure 3



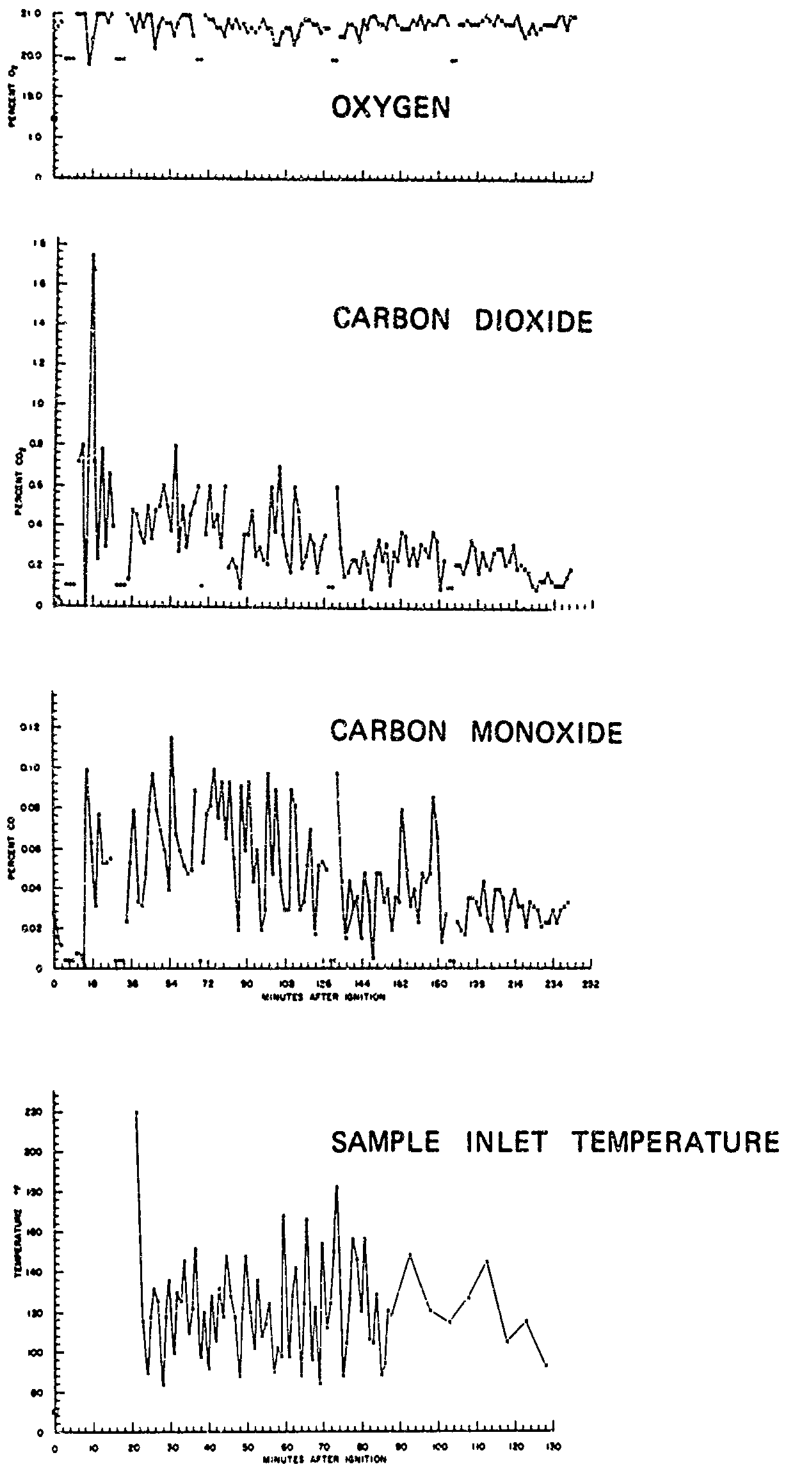
GAS ANALYSIS AND TEMPERATURE DATA – INLET NUMBER 3
U.S. FOREST SERVICE FIRE 760-12-67
SEPTEMBER 29, 1967
Figure 4



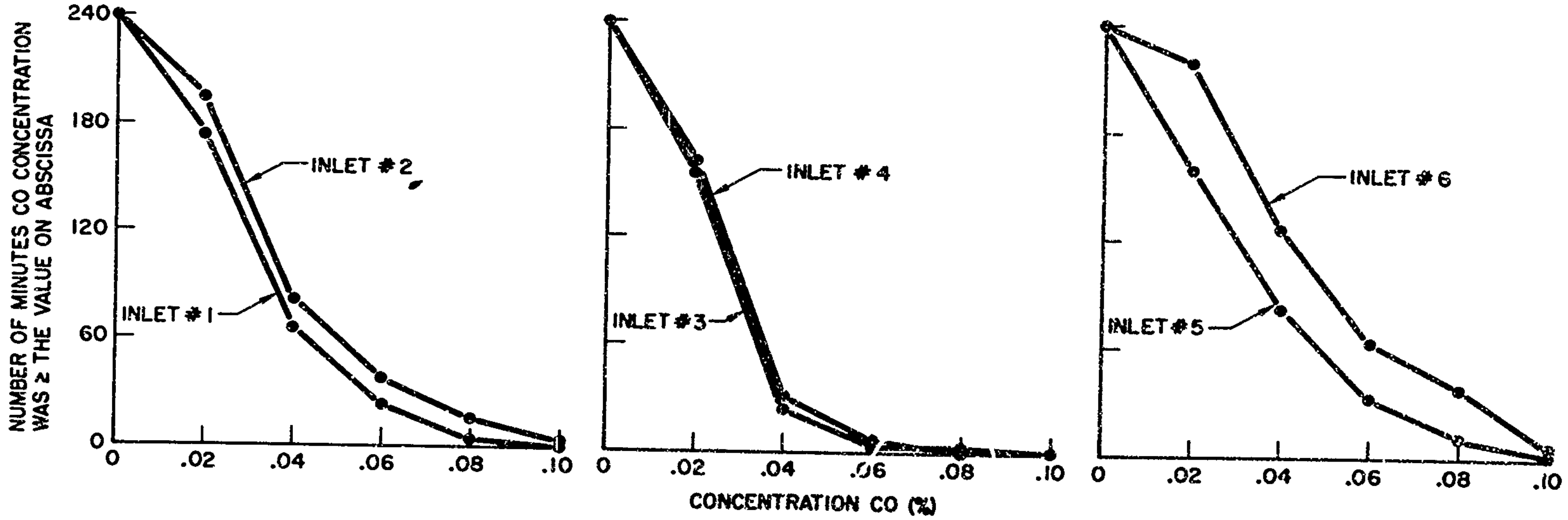
GAS ANALYSIS DATA – INLET NUMBER 4
U.S. FOREST SERVICE FIRE 760-12-67
SEPTEMBER 29, 1967
Figure 5



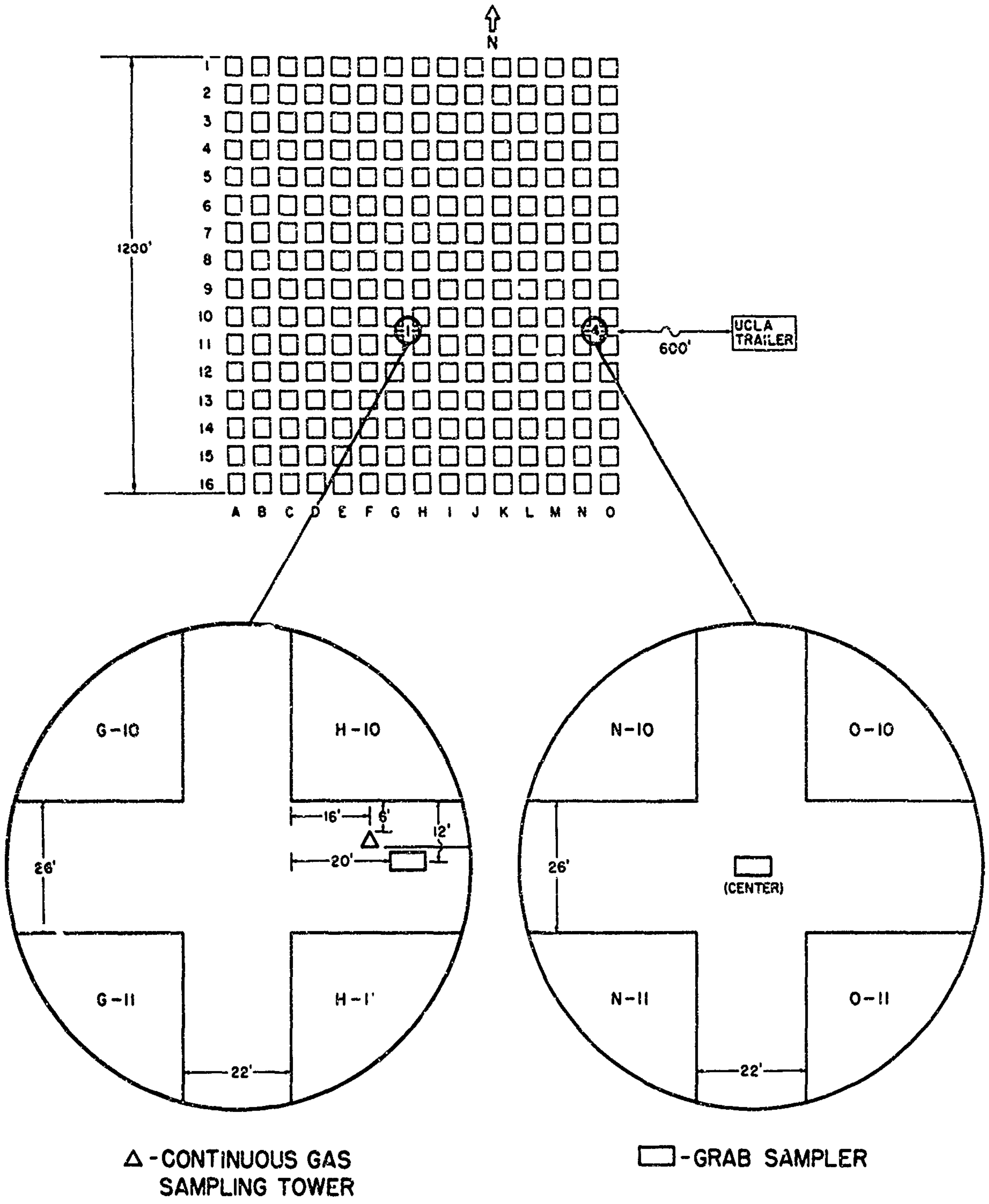
GAS ANALYSIS AND TEMPERATURE DATA – INLET NUMBER 5
U.S. FOREST SERVICE FIRE 760-12-67
SEPTEMBER 29, 1967
Figure 6



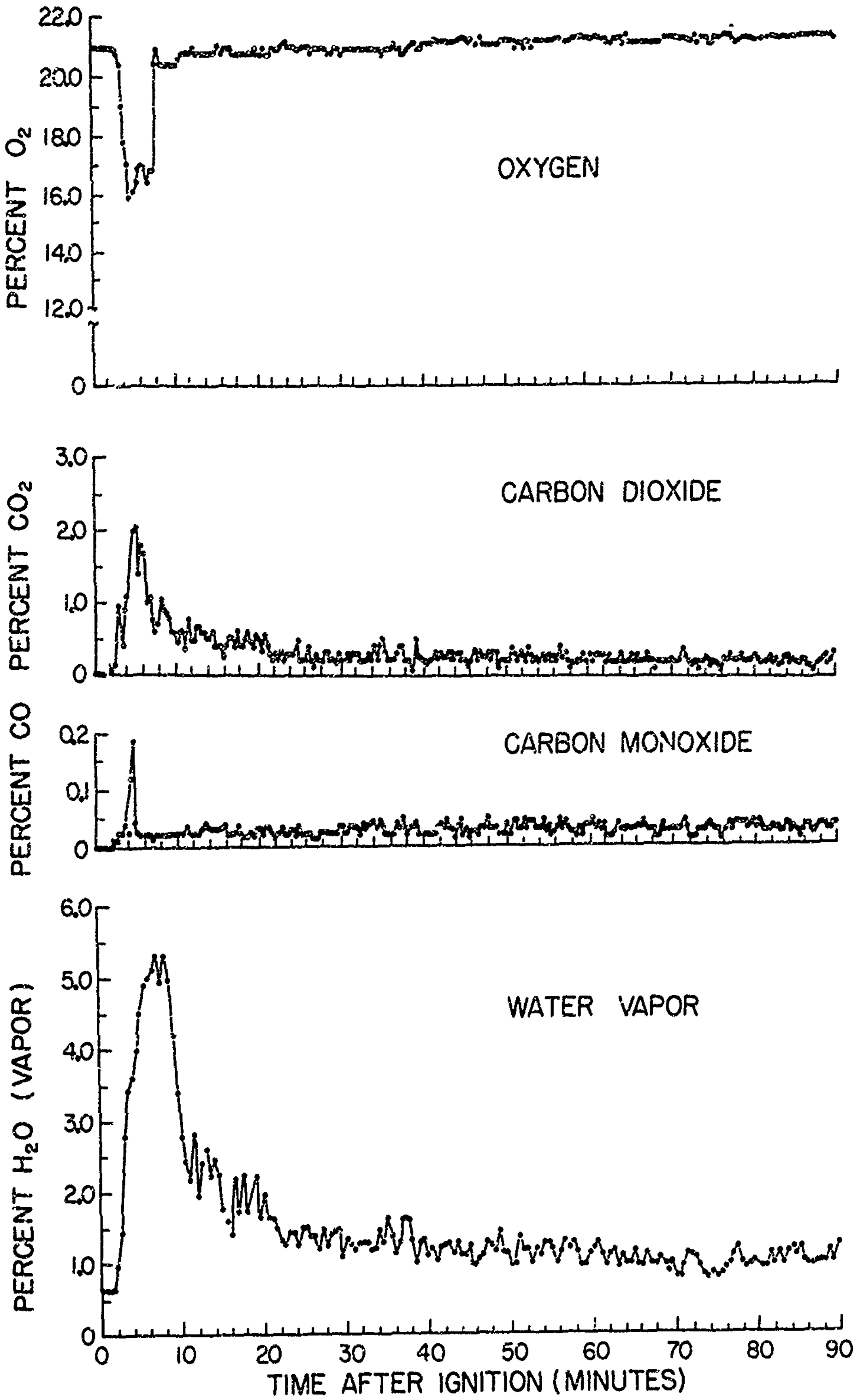
GAS ANALYSIS AND TEMPERATURE DATA – INLET NUMBER 6
U.S. FOREST SERVICE FIRE 760-12-67
SEPTEMBER 29, 1967
Figure 7



CARBON MONOXIDE EXPOSURE
FIRE NO. 760-12-67
Figure 8


N
1200'
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
A B C D E F G H I J K L M N O
1
4
600'
UCLA TRAILER
G-10
H-10
G-11
H-11
16'
6'
12'
20'
26'
22'
N-10
O-10
N-11
O-11
(CENTER)
26'
22'
Δ -CONTINUOUS GAS SAMPLING TOWER
-GRAB SAMPLER

GAS SAMPLING LOCATIONS
U.S. FOREST SERVICE FIRE 460-7-66
JUNE 14, 1966
Figure 9



Notes: (1) Data points plotted at 20 sec. intervals

(2) Instrumental uncertainities

	Concentration	Time Scale
O_2	$\pm \left\| 0.6 + .05 [O_2 \text{ meas}] \right\|$ %	± 1 minute
CO_2	$\pm \left\| 0.2 + .05 [CO_2 \text{ meas}] \right\|$ %	± 1 minute
CO	$\pm \left\| 0.04 + .05 [CO \text{ meas}] \right\|$ %	± 1 minute
$H_2O_{Vap.}$	$\pm \left\| 0.07 + .07 [H_2O \text{ meas}] \right\|$ %	± 30 seconds

(3) Pressure increase of 1" Hg from initial pressure of 20" Hg noted over test duration for O_2, CO_2, and CO analyzers. Data not corrected, therefore reflect a relative error of +5% (max). For times after ignition + 35 minutes.

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 460-7-66
JUNE 14, 1966

Figure 10

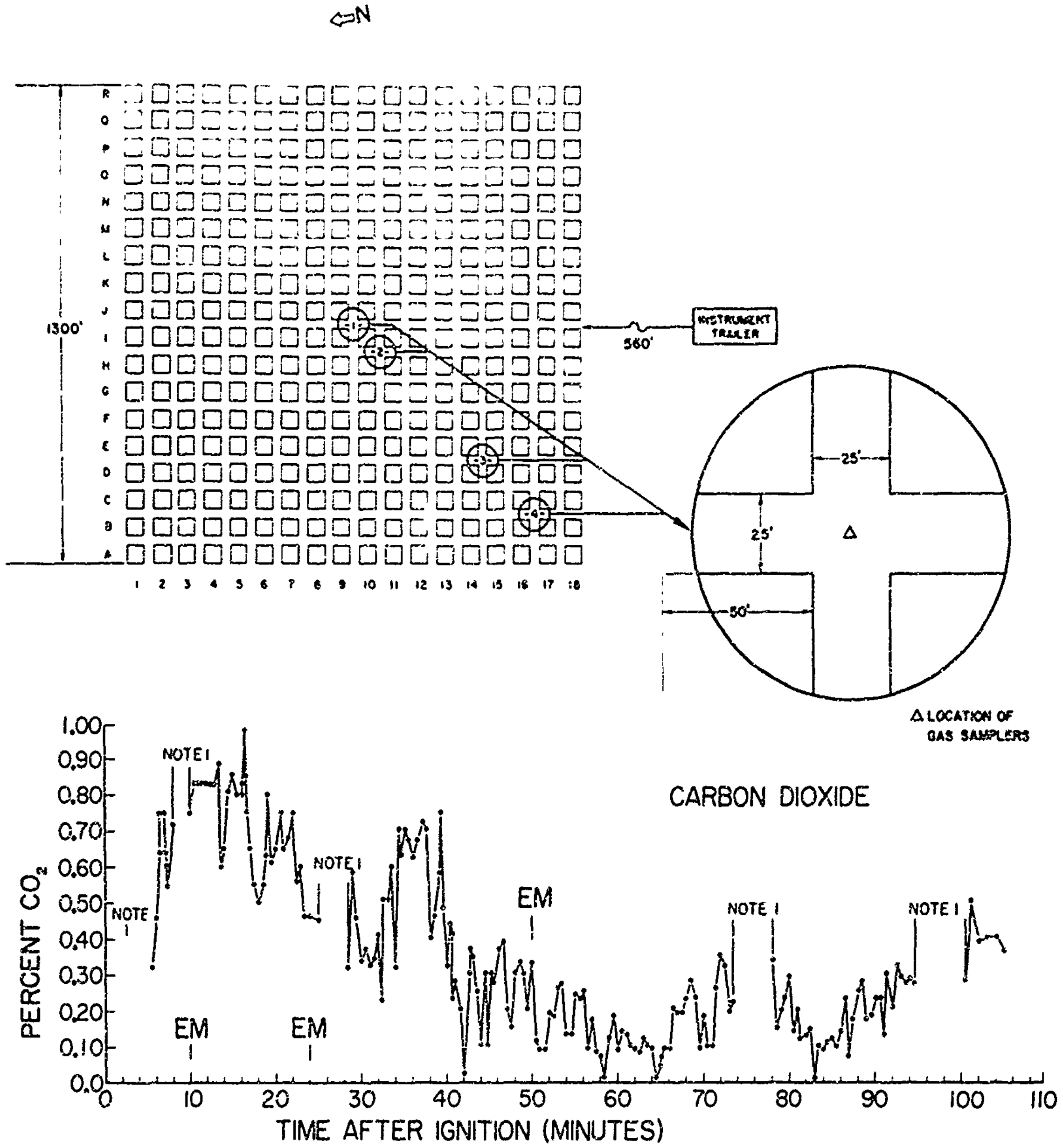
Table 1

ANALYSIS OF IMPINGER SAMPLES
U.S. FOREST SERVICE FIRE 460-7-66
JUNE 14, 1966

GAS	O_2	CO_2	CO	Aldehydes	NO	NO_2
LOCATION 1	21.0%	3700 ppm	>100 ppm	22 ppm	0.4 ppm	0.5 ppm
LOCATION 4	21.0%	1100 ppm	60 ppm	1 ppm	trace(0.1 ppm)	trace(0.1 ppm)
Method of Analysis	Gas Chromo-tography	Non-dispersive Infra-Red Analyzer		Titrametric/ Bisulfite	Modified Saltzman Method with Permanganate Oxidation of NO	
Relative Uncertainty	±5%	±10%	±10%	±25%	±25%	±25%

Note

Concentrations given are average values over time period between +1.7 minutes and +16.5 minutes after ignition.



Notes: (1) Data Discontinuities Noted as Follows

- (a) Ignition to +5 5 minutes - Pressure Adjustments
- (b) +8.0 minutes to +10.0 minutes – Recorder Malfunction
- (c) + 25 0 minutes to + 28 5 minutes – Calibration Check
- (d) + 73 5 minutes to + 78 0 minutes – Pressure Adjustments
- (e) +94.5 minutes to +100 5 minutes – Calibration Check

(2) Data points plotted at intervals varying between 10 seconds and 1 minute, dependent on rate of concentration change

(3) Instrumental uncertainty for CO_2 concentration estimated at $\pm\left[17 + .067\,[CO_2]\right]$% CO_2 where 17% CO_2 reflects calibration and reading uncertainty and 067 $[CO_2]$ is attributable to system pressure uncertainty

GAS SAMPLING LOCATIONS AND
CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 460-14-65
DECEMBER 6, 1965

Figure 11

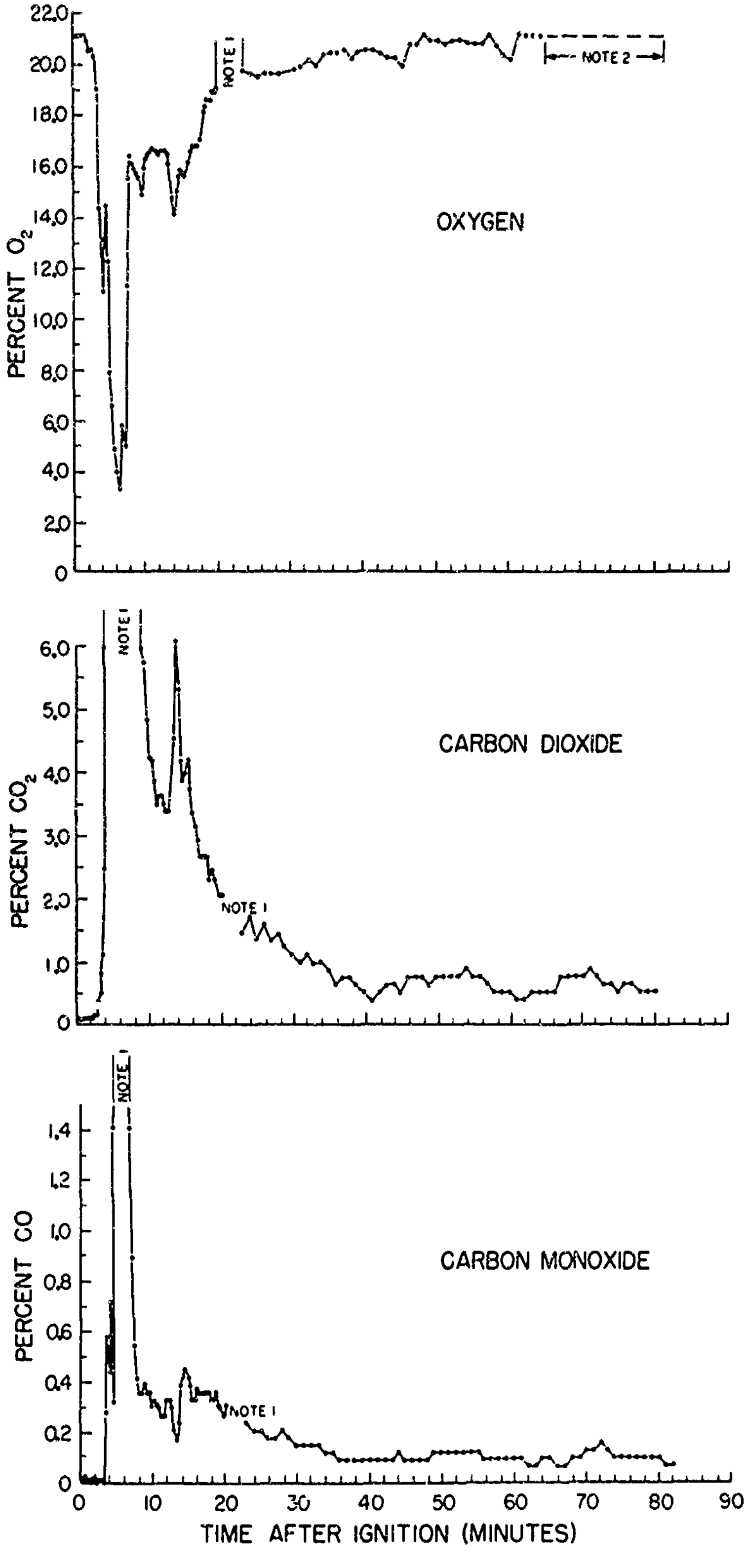
Table 2

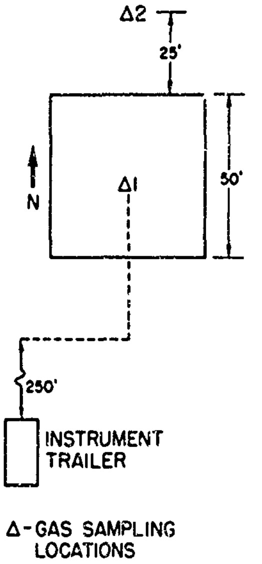
ANALYSIS OF GRAB SAMPLES
U.S. FOREST SERVICE FIRE 460-14-65
DECEMBER 6, 1965

		SAMPLING TIME – MINUTES AFTER IGNITION				
		+4	+8	+12	+20	+32
LOCATION 1	CO_2 (ppm)	500	2200	x	700	4400
	CO (ppm)	3	14	x	3	x
LOCATION 2	CO_2 (ppm)	1800	x	1300	x	x
	CO (ppm)	10	x	11	x	x
LOCATION 3	CO_2 (ppm)	1400	4600	300	x	1000
	CO (ppm)	14	31	n. d.	x	16

x - Data not available n. d. - Not detectable

Relative uncertainties estimated at ±25% for CO_2 and ±100% for CO.





Notes:

(1) Data discontinuities noted as follows

(a) Carbon Monoxide from + 5.3 to +7.0 minutes, reading off scale greater than 1.5%

(b) Carbon Dioxide from +4.3 to +9.0 minutes, reading off scale greater than 6 0%

(c) All components from +20.3 to +23.0 minutes, calibration check effecting all instruments

(2) Pressure fluctuations after +65.0 minutes introduce error in oxygen concentration reading of ± 1% oxygen. Reading is effectively 21 ± 1% over this period.

(3) Data points plotted at intervals varying between 10 seconds and 1 minute, dependent on rate of concentration change.

(4) Instrumental Uncertainties

	Concentration	Time Scale
O_2	± [0 6 + .067 (O_2 meas)]%	± 1 minute
CO_2	± [0.2 + 067 (CO_2 meas)]%	± 1 minute
CO	± [0.04 + 067 (CO meas)]%	± 1 minute

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 460-(SINGLE PILE)-65
SEPTEMBER 1, 1965
Figure 12

Table 3

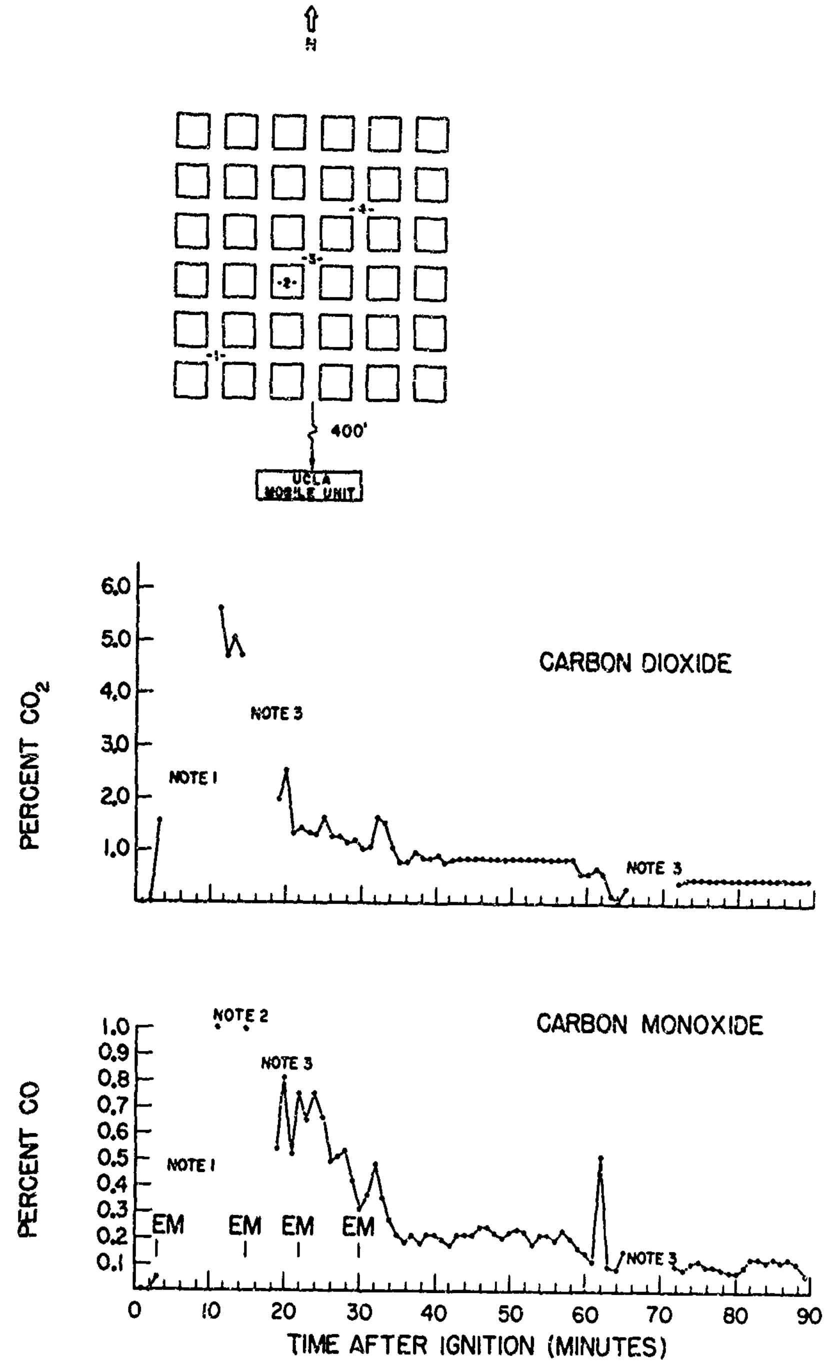
ANALYSIS OF GRAB SAMPLES
LOCATION 1
U.S. FOREST SERVICE FIRE 460-(Single Pile)-65
SEPTEMBER 1, 1965

	SAMPLING TIME – MINUTES AFTER IGNITION				
	2.0-2.5	4.0-4.5	6.0-6.5	8.0-8.5	10.0-10.5
CO_2(%)	0.2	6.3	6.8	2.6	1.4
CO (%)	.t	0.28	0.61	0.10	t

t - trace

CO_2 by Orsat Analysis, CO by Gas Chromotography

Analytical Uncertainties: CO_2, ±0.2%
CO, [0.03+0.05 (CO measured)]%



Notes:

1. System Short Circuit, all analyzers off or malfunctioning from 3.5 to 10.5 minutes
2. Carbon Monoxide off scale, greater than 1.0%
3. Calibration checks on both analyzers from + 15.0 to + 19 0 minutes and from + 66.0 to + 72.0 minutes
4. Sampling location is at ground level for carbon monoxide and dioxide

   Uncertainties

   CO ± [0.04 to .067 (CO measured)] %
   CO_2 ± [0.2 ± 0.067 (CO_2 measured)] %
5. Carbon monoxide peak at +60 0 minutes due to electrical difficulty

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 760-2-64
MAY 15, 1964
Figure 13

Table 4

ANALYSIS OF GRAB SAMPLES
LOCATION 1
U.S. FOREST SERVICE FIRE 760-2-64
MAY 15, 1964

	SAMPLING TIME – MINUTES AFTER IGNITION				
	+4	+8	+13	+18	+26
CO_2 (ppm)	3000	5000	1000	<500	<500
Saturated normal hydrocarbons to C_4 (ppm)	5	60	20	6	5

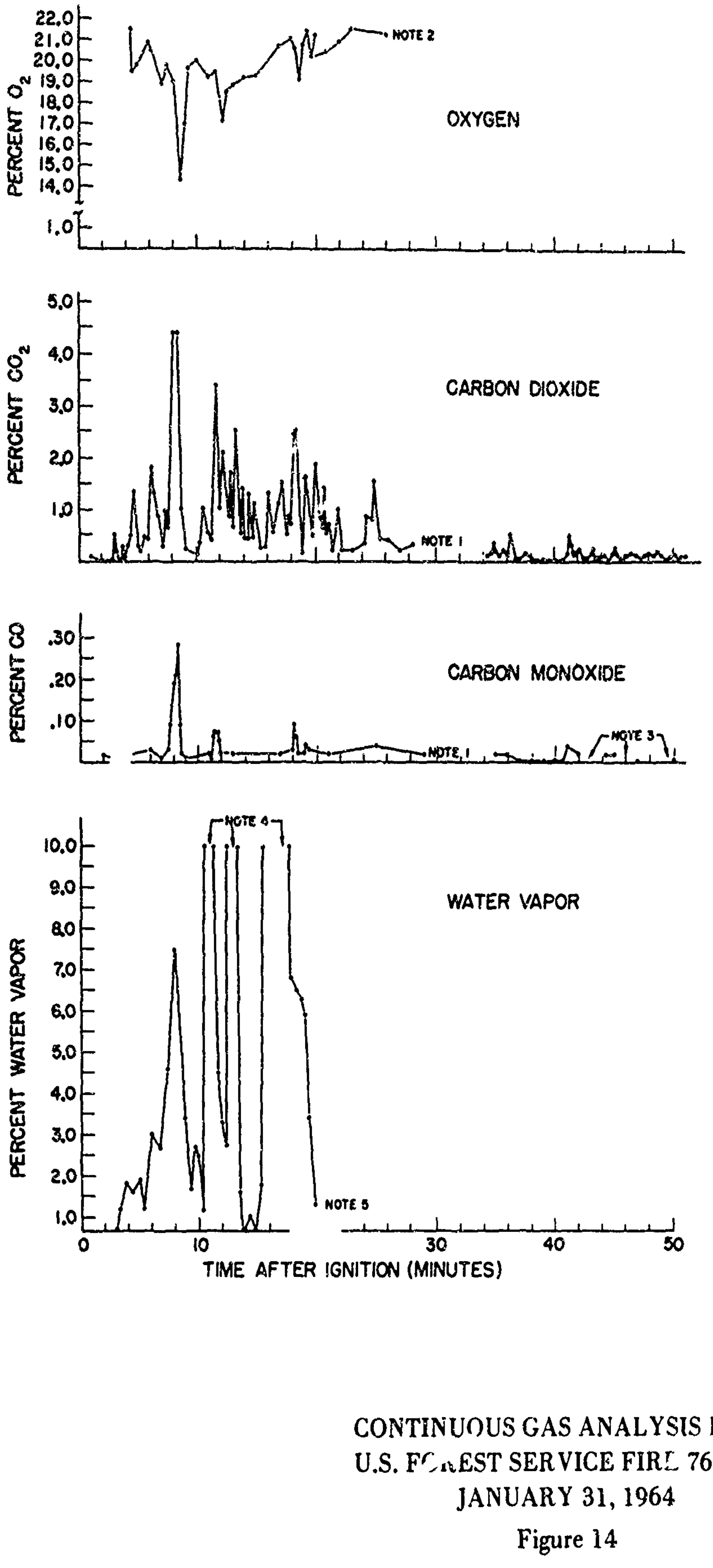
Notes:

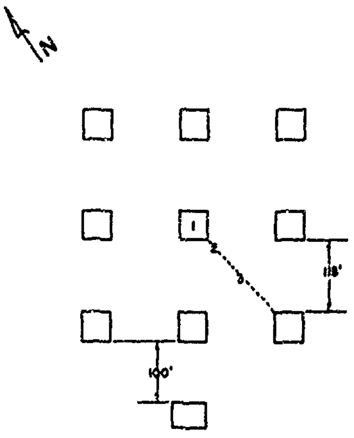
1. Uncertainties

   CO_2 ±[250+0.05 (CO_2 measured)] ppm

   Hydrocarbons ±[0.20 (hydrocarbons measured)] ppm

2. Carbon Monoxide concentrations were below 500 ppm in all samples, the limit of detectability for the method used.





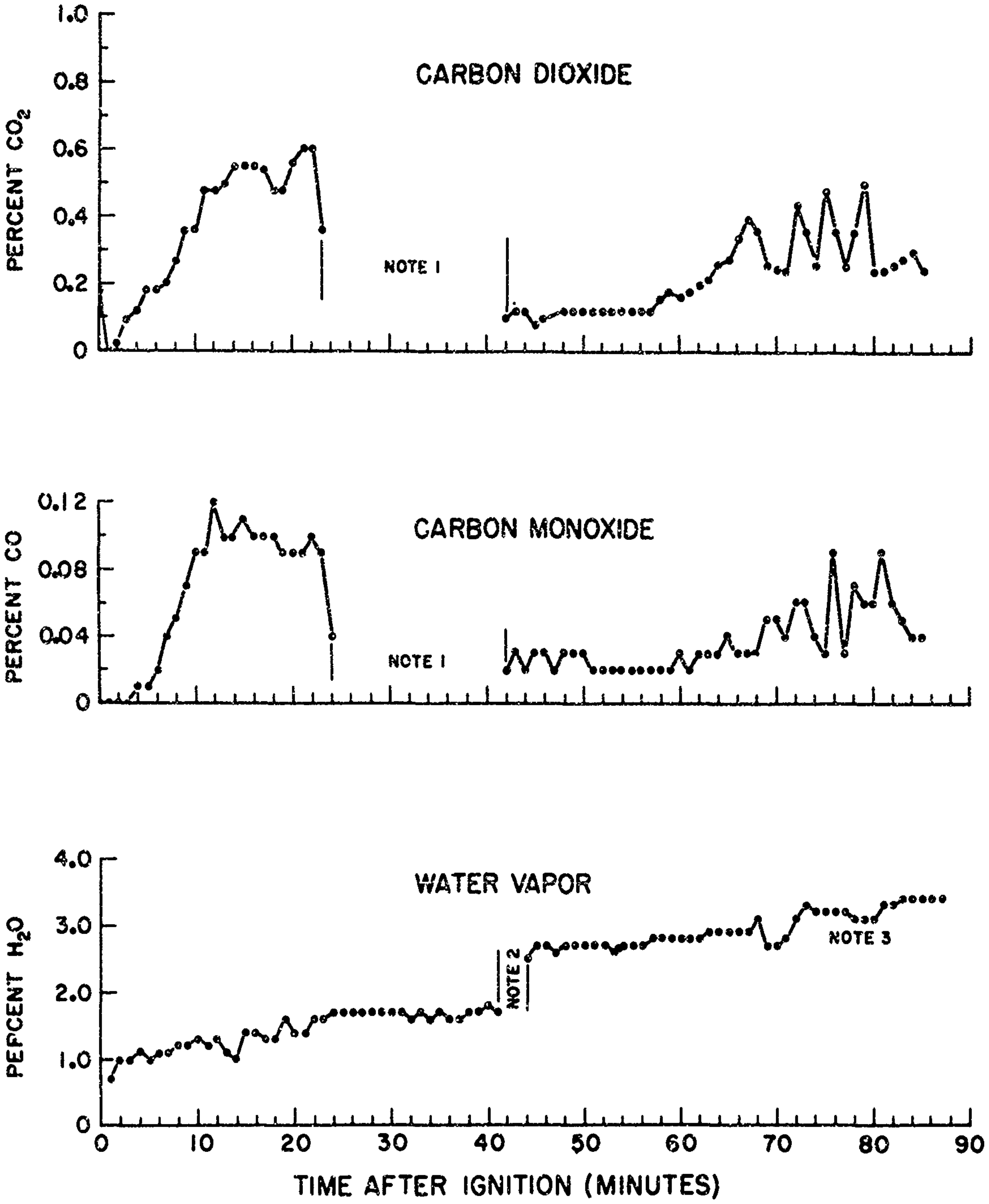
Notes:

1. + 28.0 minutes to + 33.0 minutes calibration check on instruments
2. Oxygen readings past + 26.0 minutes unreliable due to pressure variations
3. Carbon Monoxide readings past + 41.0 minutes sketchy due to recorder per malfunction
4. Water vapor readings over periods shown were off scale – greater than 10.0%
5. No water vapor data beyond 19.5 minutes due to severing of signal lines from remote instrument

Uncertainties:

O_2	± [0.67 + 0.067 (O_2 measured)] %
CO	± [0.02 + 0.067 (CO measured)] %
CO_2	± [0.2 + 0.067 (CO_2 measured)] %
H_2O	± [0.7 + 0.08 (H_2O measured)] %

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 760-1-64
JANUARY 31, 1964
Figure 14



NOTES:

1) Calibration Check on Carbon Dioxide and Carbon Monoxide Analyzer

2) Calibration Check on Water Vapor Analyzer

3) Probable Vapor Condensation in Sample Line

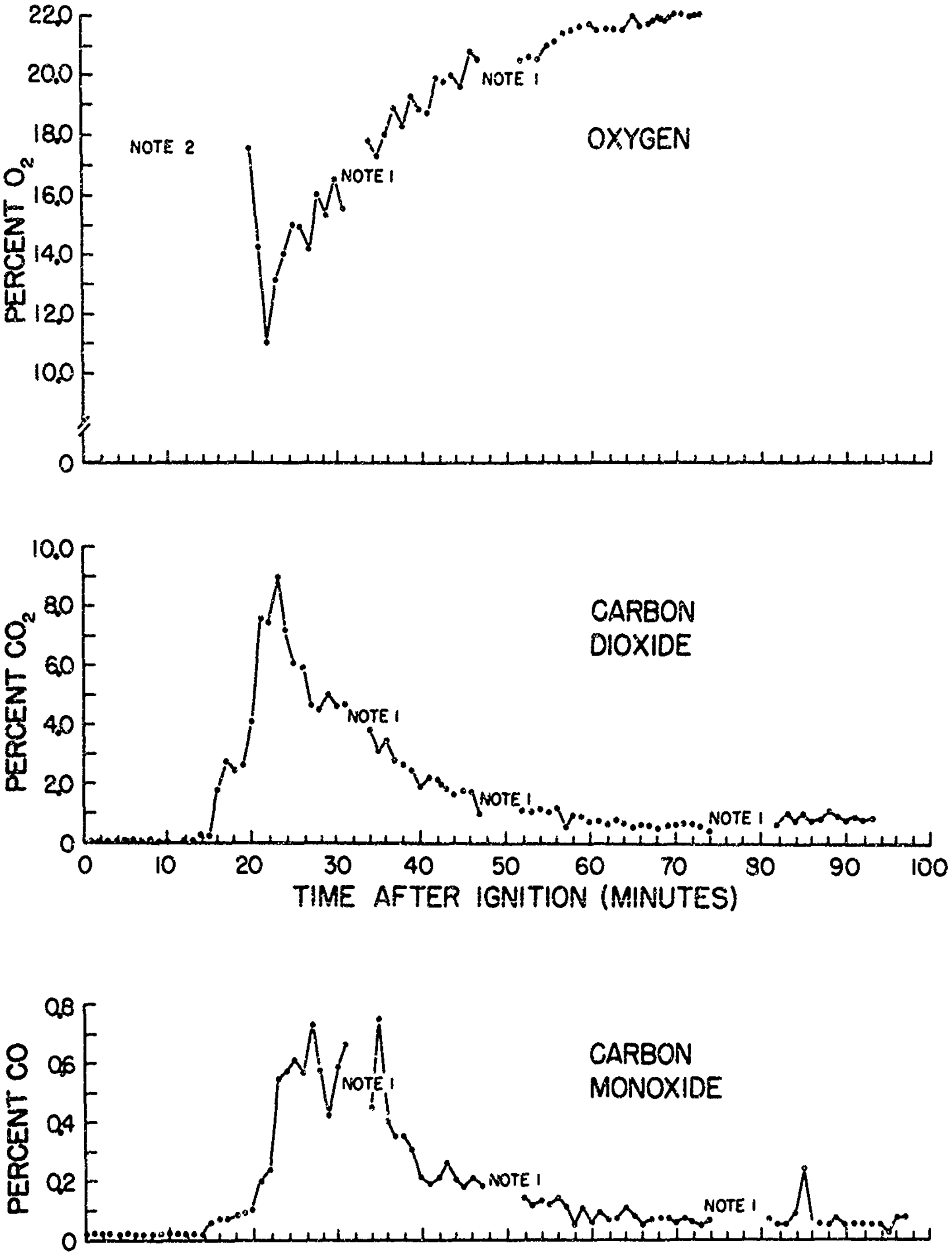
4) Uncertainties in Concentrations:

CO_2 ± [0.2 + 0.067 (CO_2 measured)] %

CO ± [0.04 + 0.067 (CO measured)] %

H_2O ± [0.07 + 0.07 (H_2O measured)] %

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 380-5-63
AUGUST 26, 1963
Figure 15



NOTES

1) CALIBRATION CHECKS ON ALL INSTRUMENTS AT +31.0, +47.0, AND +74.0 MINUTES AFTER IGNITION

2) RECORDER MALFUNCTION ON OXYGEN UNTIL +20.0 MINUTES

3) UNCERTAINTIES IN CONCENTRATIONS

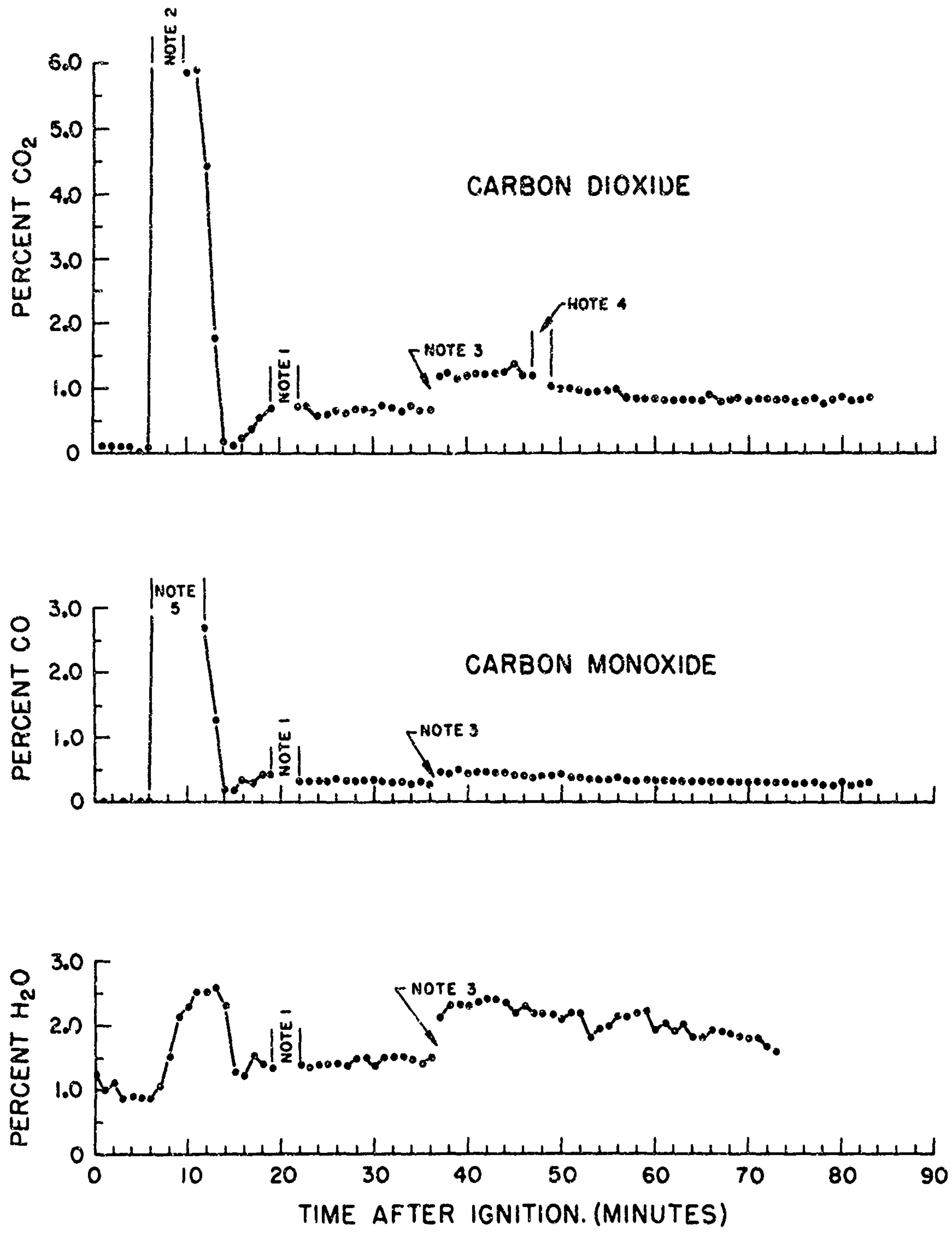
O_2 ±[0.67 + 0.067 (O_2 MEASURED)] %

CO ±[0.04 + 0.067 (CO MEASURED)] %

CO_2 ±[0.2 + 0.067 (CO_2 MEASURED)] %

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 380-3-63
AUGUST 15, 1963

Figure 16



NOTES.

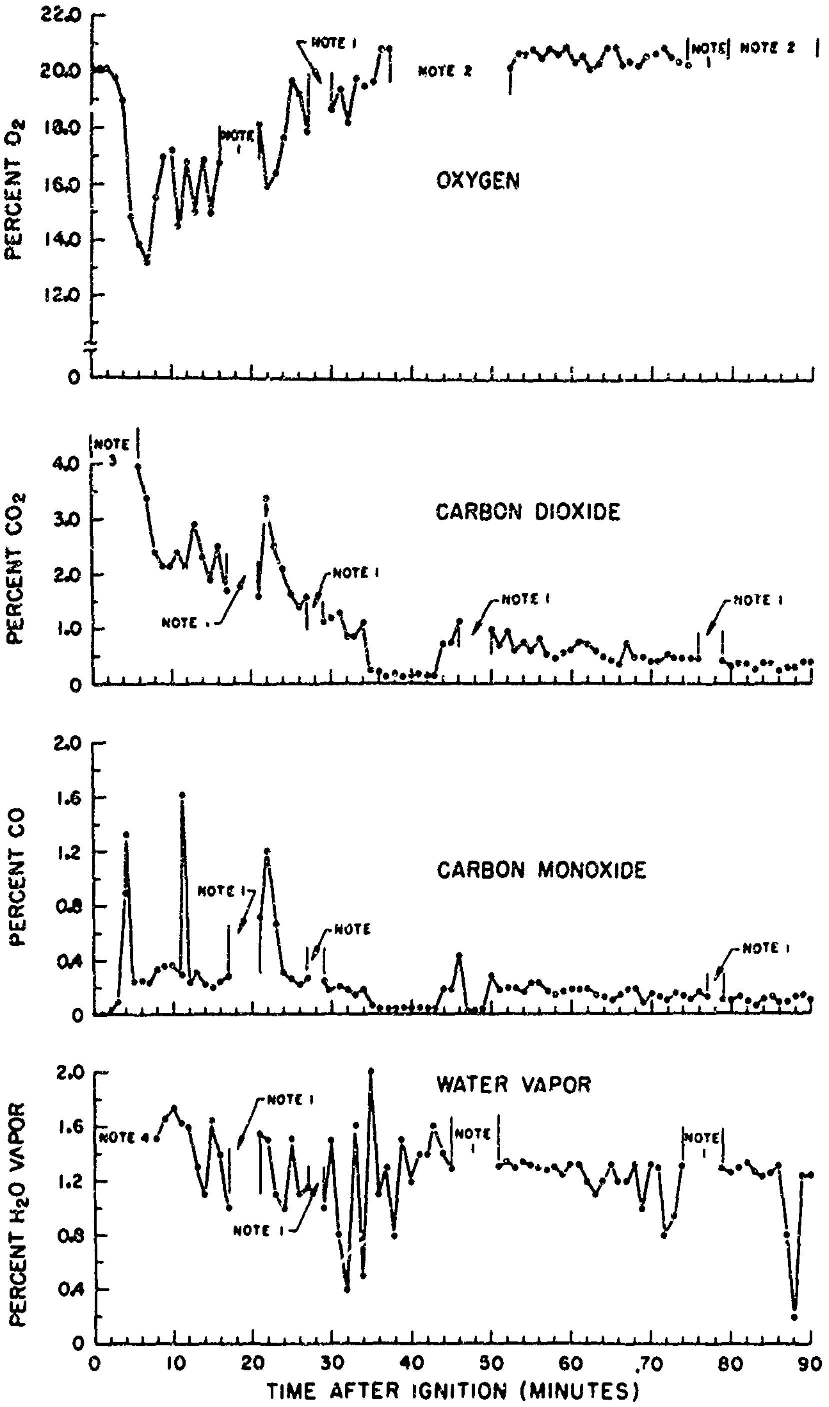
1) Calibration Check on All Instruments at +20.0 Minutes
2) Carbon Dioxide Off Scale Greater than 6.0%
3) Pressure Change on All Instruments, Data Not Corrected Reflects A +6.0 to +8.0% Relative Charge
4) Carbon Dioxide Off Scale, Probable Instrument Malfunction
5) Carbon Monoxide Off Scale, Greater than 3.0%
6) Uncertainties in Concentrations

CO_2 ±[0.2 + 0.067 (CO_2 measured)] %

CO ±[0.04 + 0.067 (CO measured)] %

H_2O ±[0.07 + 0.07 (H_2O measured)] %

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 380-2-63
AUGUST 12, 1963
Figure 17



NOTES

1) Calibration Checks on All Instruments at +18.0, +28.0, +47.0, and +76.0 After Ignition

2) Pressure Problems on Oxygen Analyzer at +38.0 and +79.0 Minutes After Ignition

3) Ignition to +6.0 Minutes No Carbon Dioxide Data

4) Ignition to +8.0 Minutes No Water Vapor Data

5) Uncertainties in Concentrations.

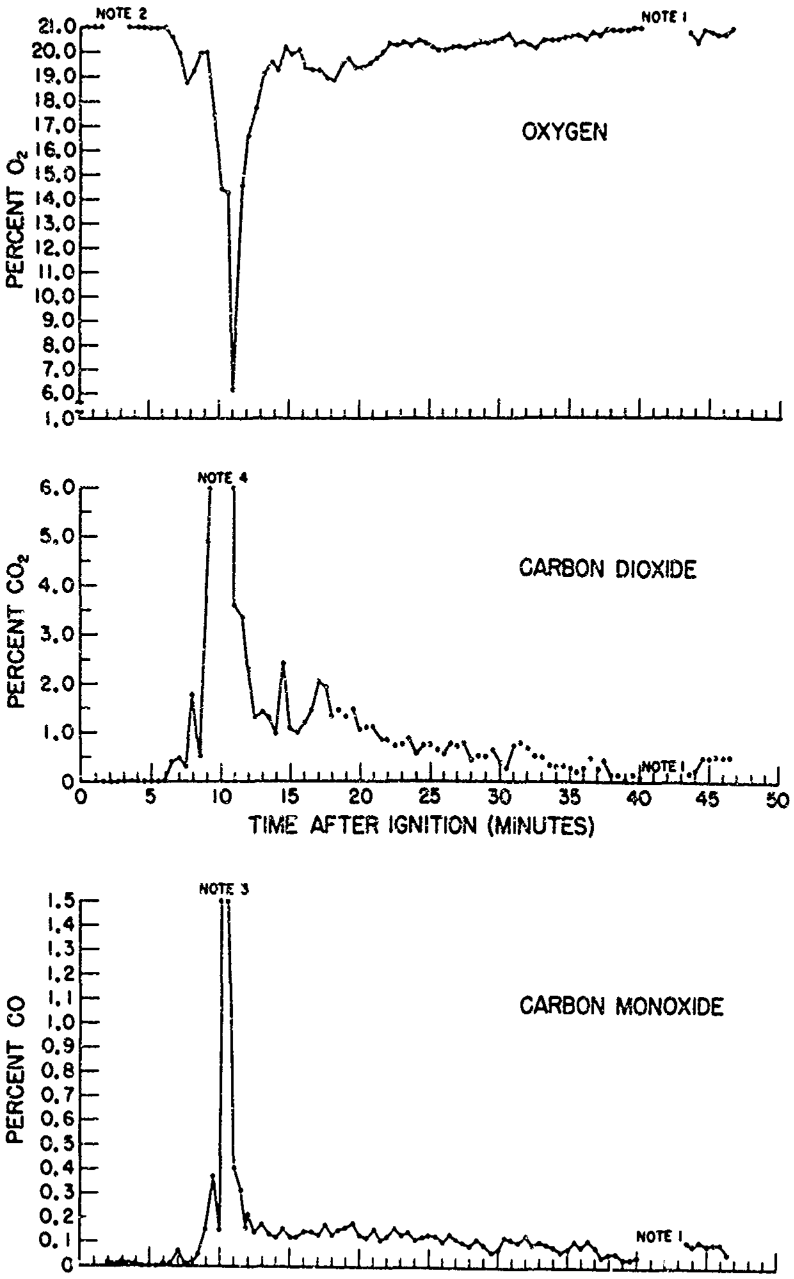
O_2 ± [0.67 + 0.067 (O_2 measured)] %

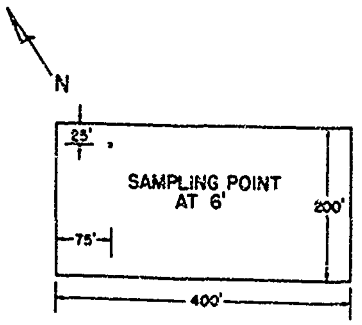
CO_2 ± [0.2 + 0.067 (CO_2 measured)] %

CO ± [0.04 + 0.067 (CO measured)] %

H_2O ± [0.07 + 0.07 (H_2O measured)] %

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 380-1-63
JULY 31, 1963
Figure 18



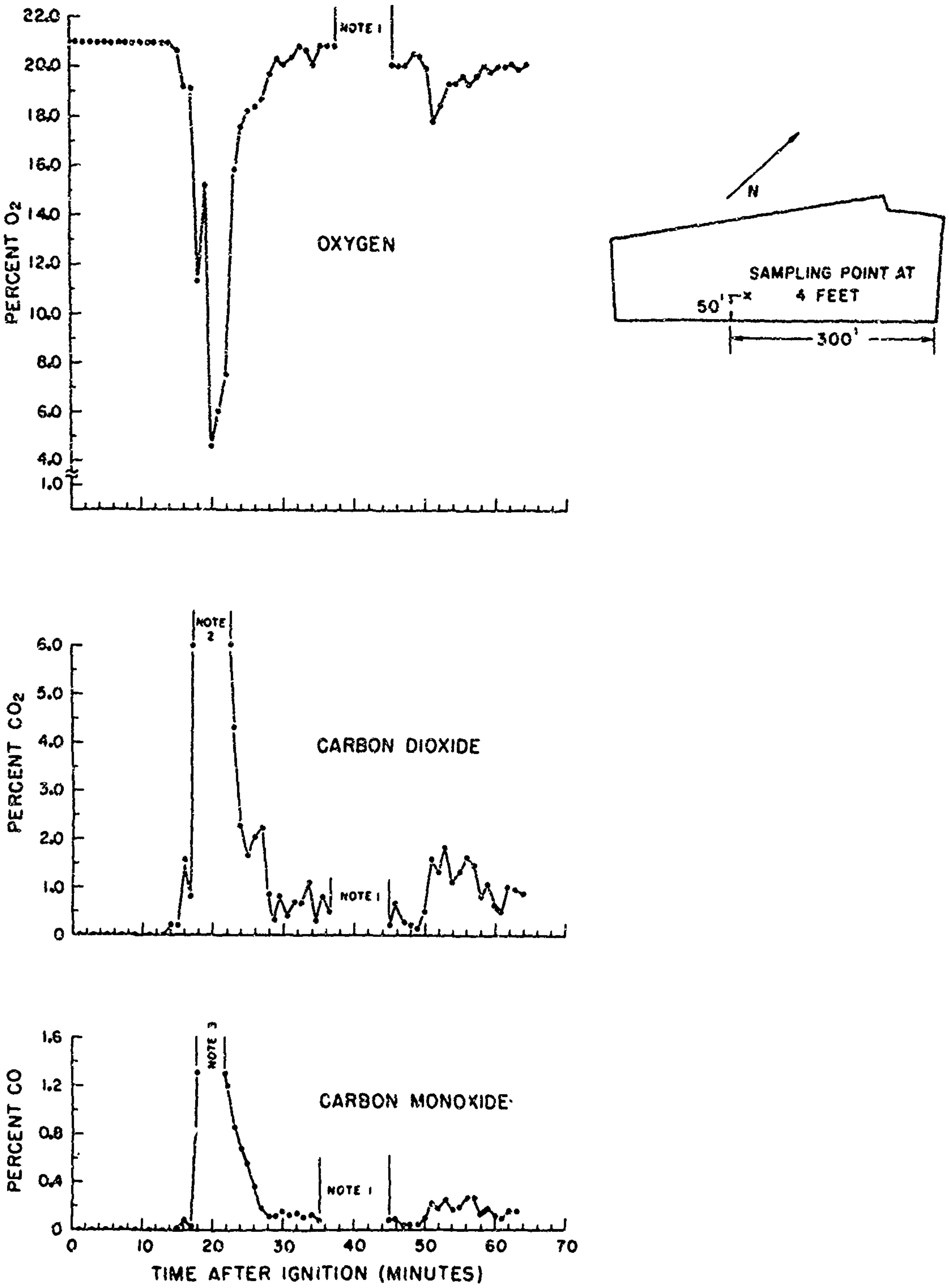


Notes:

1. Instrument calibration check on all analyzers at + 40.0 minutes
2. Pressure irregularities on O_2 analyzer from + 1.5 to + 3.5 minutes
3. Carbon Monoxide off scale (greater than 1.5%) for period shown
4. Carbon Dioxide off scale (greater than 6.0%) for period shown
5. Uncertainties

O_2 ± [0.67 + 0.0$\underline{6}$7 (O_2 measured)]%
CO ± [0.04 + 0.0$\underline{6}$7 (CO measured)]%
CO_2 ± [0.2 + 0.0$\underline{6}$7 (CO_2 measured)]%

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 428-1-63
JUNE 7, 1963
Figure 19



NOTES

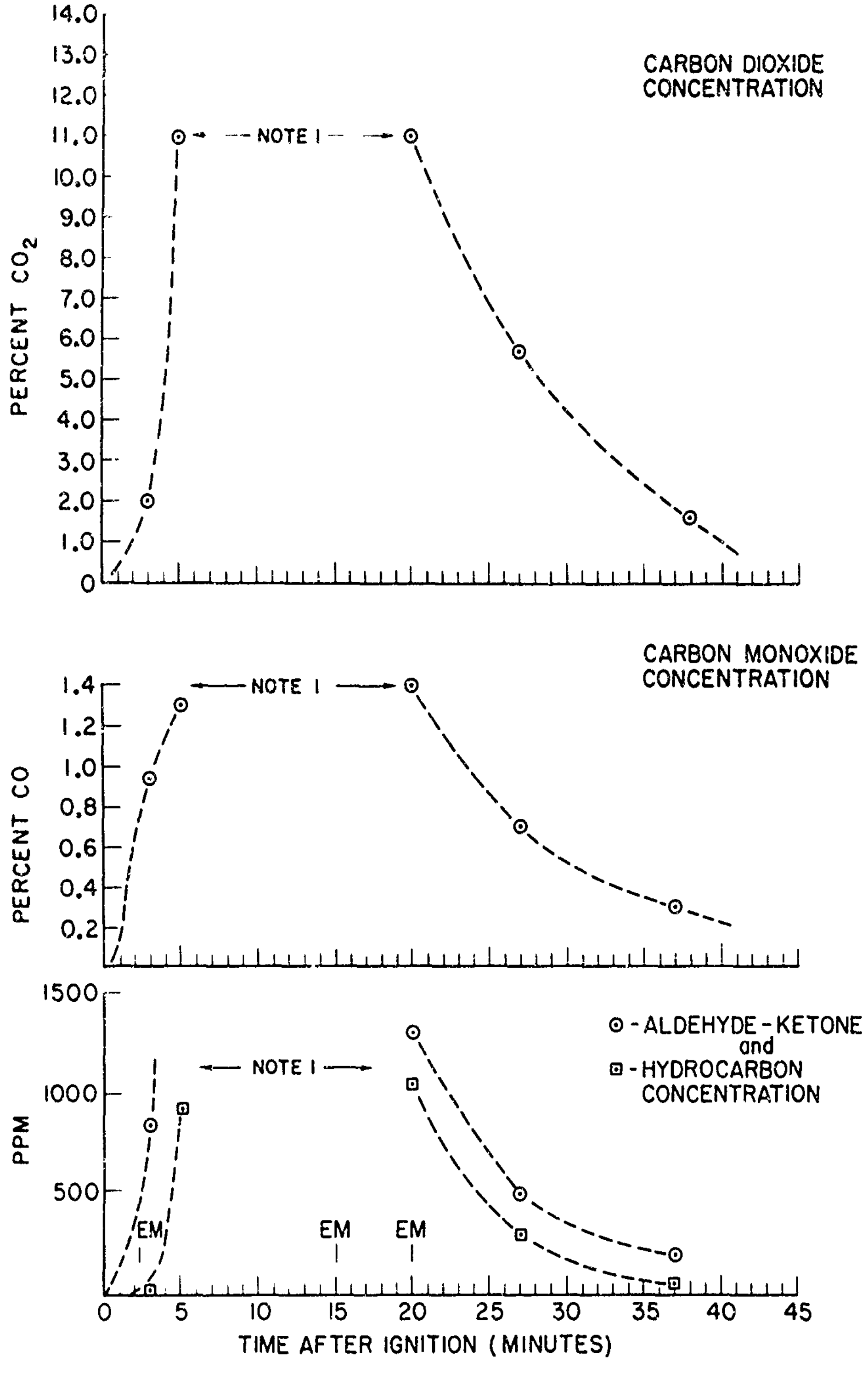
1) Calibration Check on All Analyzers
2) Carbon Dioxide Off Scale, Greater than 6 0%
3) Carbon Monoxide Off Scale, Greater than 1.5%
4) Uncertainties in Concentrations

O_2 ± [0 67 + 0.067 (O_2 measured)] %

CO_2 ± [0.20 + 0.067 (CO_2 measured)] %

CO ± [0.04 + 0.067 (CO measured)] %

CONTINUOUS GAS ANALYSIS DATA
U.S. FOREST SERVICE FIRE 428-3-63
JUNE 4, 1963
Figure 20



[illegible] this [illegible]

[illegible] performed on infra-red

[illegible] times indicated

ANALYSIS OF CONTINUOUS GAS SAMPLE STREAM
AT DISCRETE TIME INTERVALS
S FOREST SERVICE FIRE 642-1H-64
FEBRUARY 28, 1964

Figure 21

Table 5

ANALYSIS OF GRAB SAMPLES
U.S. FOREST SERVICE FIRE 760-1-64
JANUARY 31, 1964

		TIME AFTER IGNITION (MINUTES)		
		+4	+6	+7
LOCATION 1	N_2(%)	79.0	77.0	71.5
	O_2(%)	20.9	9.9	7.7
	CO_2(%)	n.d.	8.2	11.0
	CO (%)	n.d.	3.4	5.2
	hydrocarbons (to C_4)(%)	.0006	.9	2.4
		99.9	99.4	97.8
LOCATION 2	CO_2(%)	n.d.	n.d.	0.4
	hydrocarbons (to C_4)(%)	.0008	.0008	.0003
LOCATION 3	CO_2(%)	n.d.	n.d.	0.1
	hydrocarbons (to C_4)(%)	.0002	.0001	n.d.

Notes

1. Uncertainties	limit of detection (n.d.)
CO_2 ± [0.025+0.05 (CO_2 measured)] %	0.05%
CO ± [0.025+0.05 (CO measured)] %	0.05%
Hydrocarbons ±[0.2 (hydrocarbons measured)]%	< 0.00001%

2. Determined on dry basis

Table 6

CO CONCENTRATIONS

FIRE / LOCATION	Estimated Time to Peak (min)	DURATION OF CO(min)			
		> 0.16%	> 0.32%	> 0.64%	> 1.28%
Estimated Time to Danger of Death(3)		120 min	30 min	10-15 min	1-3 min
460-7 30' tower in aisle	4.4	1	N	N	N
460-14 50' tower in aisle	16.0 (1)	N	N	N	N
460-9 effective ground level	6.0	26	13	3.0	2.3
760-2 effective ground level	14.0	60	34	16	< 5
760-1 20' tower in pile	7.3	<1	N	N	N
380-3 4' in pile	23.0	29	16	2.3	N
428-1 4' -6' in pile	11.0	6.0	3.7	1.7	1.3
642-1H 5' inside	15 (2)	>37	32	21	17

N - at no time

(1) - estimated from CO_2 peak

(2) - estimate only due to sampling method used

(3) - Reference: Hamilton and Hardy

Table 7

ULTIMATE ANALYSIS (Wood Samples)

U.S. Forrest Service Fire 460–(Single Pile)–65

September 1, 1965

	Hydrogen %	Carbon %	Oxygen %
Needles			
Top center 1/8"	6.03	53.10	
Top outside	6.93	52.69	
Bottom center	7.36	54.93	
Bottom outside	6.94	52.69	
Average (4 run)	6.81	53.35	39.84
Roots			
Bottom outside 1"-2"	6.58	48.67	
Bottom center 1/2"	7.37	52.12	
Bottom outside 1/4"-1/2"	6.22	47.35	
Bottom center 1"-2"	5.72	47.97	
Branches			
Bottom center 1"-2"	5.45	49.04	
Bottom outside 1"-2"	6.59	50.65	
Bottom outside 1/4"-1/2"	6.72	51.20	
Bottom center 1/4"-1/2"	5.69	48.46	
Top outside 1/4"-1/2"	6.59	48.91	
Top center 1"-2"	5.78	49.53	
Top outside 1"-2"	5.85	50.38	
Top center 1/4"-1/2"	6.71	50.82	
Average (12 run)	6.27	49.59	44.14

$C_{49.59}$	$H_{6.27}$	$O_{44.14}$	
$\div 12 = 4.133$	$\div 1.008 = 6.22$	$\div 16 = 2.759$	
$\times 1.452 =$	$\times 1.452 =$	$\times 1.452$	
$C_{6.00}$	$H_{9.03}$	$O_{4.006}$	$C_6H_9O_4$

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